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Reliability Formulation for the Strength and Fire Endurance of Glued-Laminated Beams

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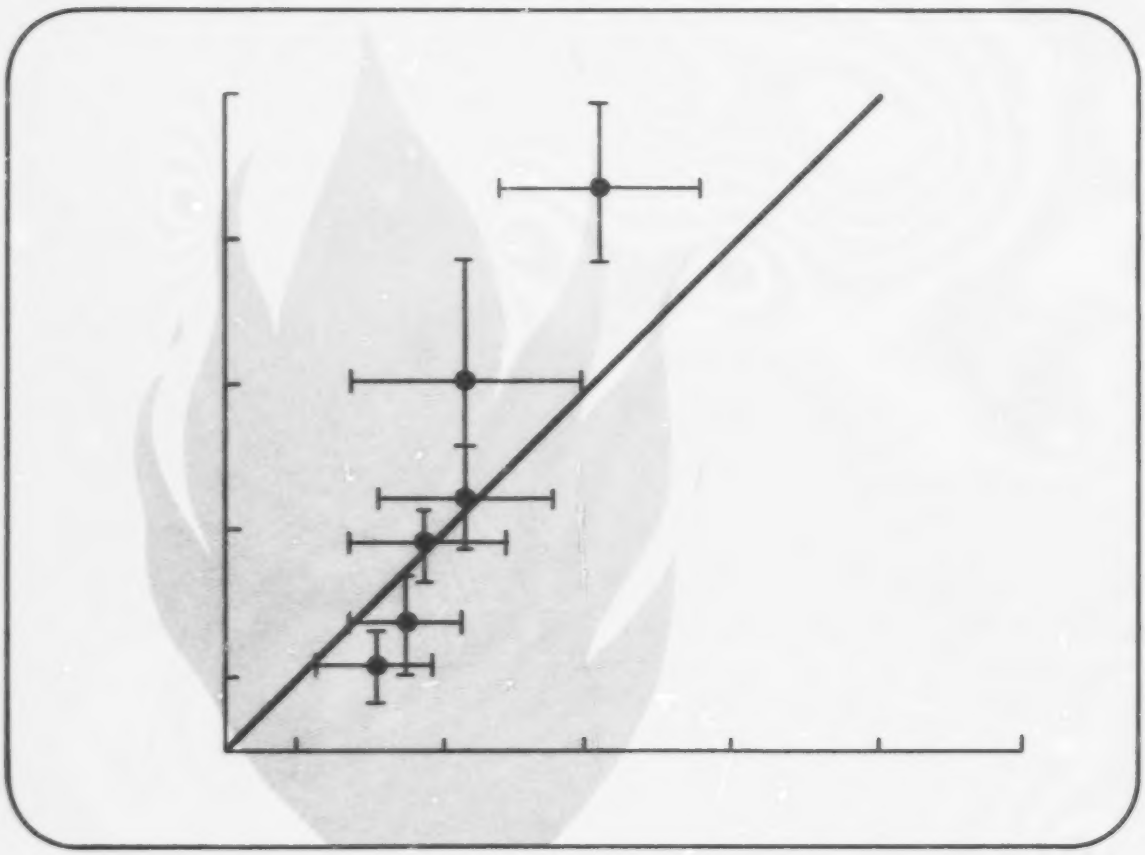

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Abstract

A model was developed for predicting the statistical distribution of glued-laminated beam strength and stiffness under normal temperature conditions using available long span modulus of elasticity data, end joint tension test data, and tensile strength data for laminating-grade lumber. The beam strength model predictions compared favorably with test data for glued-laminated beam strength data with 8 and 10 laminations; however, the model predicted strength values 30 percent higher for glued-laminated beam strength data with 4 laminations.

Fire endurance and structural resistance were evaluated by artificially reducing the cross section. This reduction accounts for char depth as well as for reduced wood strength caused by the elevated temperature. Average time-to-failure predictions using the developed model compared well with those from conventional prediction methods.

Keywords: Glulam, beams, fire endurance, strength, model, reliability, testing.

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Reliability Formulation for the Strength and Fire Endurance of Glued-Laminated Beams

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Introduction

The goal of this research was to develop a reliability-based model to predict the strength of glued-laminated (glulam) beams under normal temperature conditions and then extend the model to predict the time to failure for fire-exposed beams. Before the analysis is described in detail, a brief historical account of the evolution of laminated timbers and their performance is provided.

Structural glulam timber is an engineered, stress-rated product of a timber-laminating plant, comprised of suitably selected and prepared wood laminations securely bonded together with adhesives (*1*).[4] Before the advent of structural glulam timber, solid timbers were used. These massive, solid members were used extensively in New England textile mills, which accounts for the name "mill construction" (*20*). Historically, heavy timbers have exhibited a natural resistance to fire, due to minimal combustible surface area as well as low thermal conductivity. In addition, the char layer which forms on the surface of the timber provides another thermal barrier.

As the demand for heavy timbers increased, the availability of trees large enough to supply them declined, and laminated timbers were developed. These timbers, comprised of several smaller pieces of lumber, displayed the same natural resistance to fire as solid timbers.

In time, a special "heavy timber" fire rating for mill-type construction evolved, based on the assumption that these timbers could support their full design load under fire exposure for 1 hour. However, these ratings have been based on historical evidence from actual fires rather than on a uniform time rating system. One of the goals of this study was to provide the base for a more rational method of assigning fire ratings for timber beams.

This paper deals specifically with laminated beams which are loaded in bending. Several studies (e.g., *16, 23, 26, 28, 37*) have indicated that bending failures usually initiate in the outer tension zone and that glulam generally exhibits elastic behavior to failure. Based on this information, a computer model was developed and checked for its ability to predict failure in the tension zone of the laminated beams both at room temperature and under simulated fire exposure.

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Conventional Glulam Beam Strength Prediction

Bending strength of glulam beams is greatly affected by the strength-reducing characteristics found in the wood. Traditionally, researchers have tried to describe beam strength by beginning with clear wood flexural properties and then applying strength-reduction factors to account for these characteristics. The most popular approach to bending strength prediction has been a method which utilizes a ratio of moments of inertia, I_K/I_G, to arrive at a reduction factor to account for the effect of knots on bending strength (*17*).

The basic concept of the I_K/I_G method is described as follows: I_K is the sum of the moments of inertia of the cross-sectional areas of all knots within 6 inches of a single cross section of a beam; I_G is the moment of inertia of the full or gross cross section. Equations relating the ratio I_K/I_G to bending strength and stiffness have been empirically derived (*17*). The strength-reduction factor obtained from these equations is then directly applied to the clear wood flexural properties. A detailed discussion of the procedures involved in the I_K/I_G prediction method is found in USDA Technical Bulletin 1069 (*17*).

Discrepancies between actual test values and predicted I_K/I_G bending strength values have been noted (e.g., *28*). Research has been conducted at the U.S. Forest Products Laboratory to refine the I_K/I_G method by providing supplemental criteria for specially graded tension laminations to ensure the I_K/I_G method was applied as originally intended (*9*).

Strength-prediction methods other than I_K/I_G have been attempted on shallow laminated beams. Marx and Moody (*26*) found that an alternate prediction method based on a strength ratio concept was the most accurate predictor of bending strength for shallow glulam beams of a uniform grade.

The conventional glulam strength-prediction methods formed the basis for ASTM D 3737 (*6*), the basic reference for current industry standards (*2*). These methods were used to predict design bending strength values; consequently, emphasis was not placed on defining the entire statistical distribution of bending strength.

Recent Innovations in Glulam Beam Strength Prediction

Because the previously discussed prediction methods were not concerned with entire statistical distributions, they are not well suited for probabilistic design methods which require that information to be known. Recent research efforts have attempted to incorporate a probabilistic framework into beam strength-prediction models. One such model has been developed by Foschi and Barrett (*16*), who used computer simulation to estimate the distribution of beam strength. Their model is based on the assumptions that failures of glulam beams initiate in the tension zone and that there is elastic behavior to failure.

The Foschi-Barrett (*16*) model employs a combination of Monte Carlo simulation, strength-reduction factors, and finite element analysis. A brief outline of their procedure follows:

1. End joint locations and associated tensile strengths are assigned.

2. Clear wood flexural properties are randomly generated using the two-parameter Weibull probability density function.

3. Various factors are applied to clear wood flexural properties to account for knot size and location as well as load sharing between adjacent laminations.

4. Finite element analysis is used to predict failure in the tension zone. Knots are represented by cracks in the finite element scheme.

5. The ultimate bending stress is recorded and steps 1, 2, 3, and 4 are repeated until sufficient data have been generated.

6. The statistical distribution of bending strength is then estimated using the data from step 5.

Available data indicate that the Foschi-Barrett model can predict beam strength with reasonable accuracy. However, this model is rather complex, and is based on the assumption that the flexural properties of actual lumber can be estimated from clear wood flexural properties with reduction factors applied.

Another rational alternative to classical beam strength prediction is contained in a computer model by Brown and Suddarth (*13*). In this model, Monte Carlo samples of modulus of elasticity (E) are drawn from distributions according to grade and then a transformed section analysis is performed to calculate gross E and the allowable moment carrying capacity of the beam.

The Brown-Suddarth (*13*) model was intended as an aid to design; hence, allowable fiber stresses were used rather than ultimate stresses. Apparently, no attempt was made to validate the model with respect to ultimate bending strength. The model's intrinsic appeal comes from the fact that actual E values for the lumber are used in the simulation rather than clear wood properties. The model is limited in that the effect of end joints is not included. Hence, the same set of flexural properties is used for the entire length of each lamination.

Larsen (*23*) is also conducting research to determine the strength and stiffness of glulam beams with finger joints included in the analysis. He has modeled mechanical properties of lumber used in glulam and is developing a theory for the strength of glulam based on properties of the constituent lumber.

Most of the recent innovations in predicting glulam strength utilize computer simulation models. Although the approach taken for each model varies, their common goal is to establish the statistical distribution of strength for use in probabilistic design.

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Fire Endurance

The fire endurance of a structural member is defined as its ability to withstand exposure to fire without loss of its load-bearing function. As previously stated, heavy timbers (minimum dimensions are 6 by 10 in. nominal) have often been assigned a 1-hour fire rating, based on historical evidence. A more rational approach to fire rating was provided with the advent of widely accepted standard ASTM E 119 (*7*). This standard describes a procedure whereby full-scale components are subjected to controlled fire conditions that produce a given ambient temperature over time (*35*). The ASTM E 119 time-temperature curve is shown in figure 1. It should be noted that the standard fire test of ASTM E 119 is not intended to describe actual fires, which grow and decline in intensity with the passage of time. The primary function of ASTM E 119 is to prescribe a standard fire exposure for comparing the performance of various building materials and construction assemblies.

One of the major differences between solid timber and glulam is the presence of glue lines between the laminates. The behavior of these glue bonds when exposed to fire is of great importance. Schaffer (*36*) and Wardle (*40*) claim that thermosetting synthetic resin types of adhesives, such as phenol or phenol-resorcinol, retain their bond during fire, with final destruction coming from charring at about the same rate as timber. Wardle concludes that structural glued-laminated timber is similar to solid timber with respect to fire endurance when such adhesives are used.

Fire Endurance Prediction

The most common fire endurance prediction methods assume a constant char rate and simply calculate the amount of wood consumed during some interval. The strength of the uncharred beam cross section is then calculated using classical beam bending theory. Finally, a strength-reduction factor is applied to account for the temperature and moisture increase in the residual wood, along with a factor for load conditions (*22*, *24*, *35*).

The following assumptions are necessary to predict fire endurance by the previously mentioned methods:

1. The member is exposed to standard fire conditions, as in ASTM E 119.

2. The residual cross section is rectangular in shape during fire exposure.

3. The ratio, k, of allowable bending strength to ultimate bending strength before fire is known.

4. The ratio between the fundamental strength properties of the beam after and before the fire equals α.

5. The rate of charring can be approximated by a constant average value β.

The time to failure is measured up to the point where the allowable bending moment for the design load equals the ultimate bending moment of the charred beam. Based on these assumptions, Imaizumi (*22*) derived the critical residual depth, d, for a beam that is heated on all four sides:

$$\left(\frac{k}{\alpha}\right)\frac{B/D}{d/D-(1-B/D)}=\left(\frac{d}{D}\right)^2 \qquad [1]$$

where

B = initial width of beam
D = initial depth of beam
k, α as previously defined

The time to reach the critical depth for char rate β is given by:

$$t_c=\frac{(D-d)}{2\beta} \qquad [2]$$

Imaizumi (*22*) has provided graphs of safe burning times for beams loaded to their full allowable bending stress (fig. 2). The strength-reduction factor, α, was assumed to be unity.

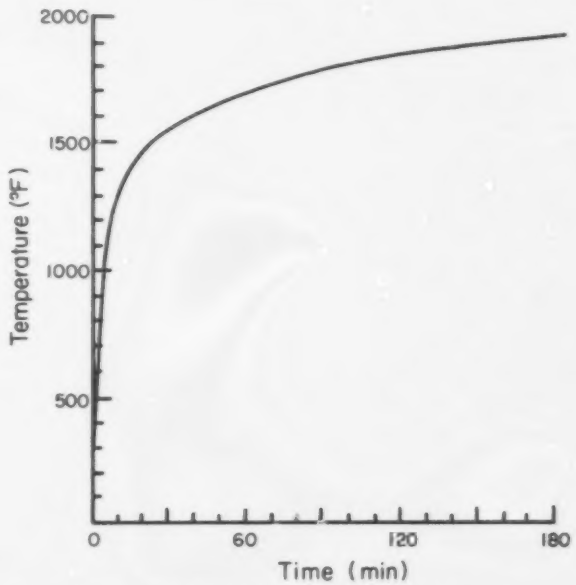

Figure 1.—The ASTM E 119 time-temperature curve (9). (ML85 5220)

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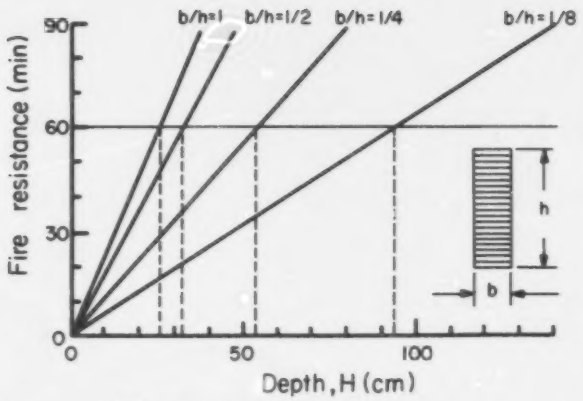

Figure 2.—Anticipated fire endurance for beams loaded to 100 percent of the design load. The temperature reduction factor is equal to unity, and the beams are exposed to fire on all four sides (28). (ML85 5221)

The factors k and β can be estimated from well established references. For example, k for bending stress is assumed to equal 0.476, ASTM D 2915 (*5*). The most widely accepted value of char rate, β, is approximately 1/40 inch per minute (*22,24,30,34,39,40*). The char rate remains fairly constant throughout the fire. However, there is little agreement as to the appropriate value of the strength-reduction factor, α. Imaizumi (*22*) and Odeen (*29*) estimate the range of α to be about 0.80 to 0.90. Lie (*24*) recommends using a value of 0.80. Wardle (*40*) reports that New Zealand has adopted a reduction factor of 0.50. Owing to the fact that most fire tests of beams have been terminated before failure due to load occurred, no universally accepted values for k and α have been established (*35*).

Lateral torsional buckling is an important consideration in fire endurance prediction, since the depth-to-width ratio is continually changing due to the reduction in beam cross section. The risk of buckling is also increased if intermediate supports fail during fire exposure (*18*). Imaizumi (*22*) was the first to recognize the importance of lateral torsional buckling and incorporate it into a fire endurance model. He states that lateral buckling may occur when the ratio of b/d reaches a critical value of r. The time to failure for this situation is given by:

$$t_c = \frac{D(B/D - r)}{2\beta\,(1 - r)} \qquad [3]$$

The value of r depends on a number of factors, including support conditions and type of loading. Values of r have not been determined to date.

In a more effective way, Fredlund (*18*) outlined a procedure for designing fire-exposed laminated beams with respect to lateral buckling. He followed the same basic procedure of predicting fire endurance outlined by Imaizumi, but used a lateral buckling equation derived by Pettersson (*32*).

Pettersson's equation for the critical moment in bending is given by:

$$M_{cr} = \frac{m}{L}\sqrt{\frac{EI_yGJ}{(1 - I_y/I_x)(1 - GJ/EI_x)}} \qquad [4]$$

where

EI_y = bending stiffness about weak axis of section
GJ = torsional stiffness of section
I_y/I_x = ratio of moments of inertia of section about weak and strong axes, respectively
L = unsupported length of the beam

The coefficient m is dependent on load and support conditions. For example, m equals 28 for a simply supported beam under a uniform load. Values of m for other load and support conditions have also been established (*32*).

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Monte Carlo Simulation

Monte Carlo simulation is a method for obtaining information about system performance from component data. Monte Carlo simulation is useful in analyzing system response when the component variables are described by complex and intractable functions. Basically, a Monte Carlo analysis requires the statistical distribution of each component variable and the relationship between the component variables and system performance. If these two things are known, then it is unnecessary to physically build the system; rather, high-speed digital computers can be used to evaluate system performance through many replications of the experiment. The degree of accuracy obtained by a Monte Carlo simulation depends on the accuracy of the statistical distributions of the component variables and the correctness of the functional relationships between the component variables and system performance. Due to the random nature of the simulation, the accuracy also depends on the number of trials in the simulation. A flow chart of the Monte Carlo simulation method, obtained from Hahn and Shapiro (*21*), is shown in figure 3.

Monte Carlo simulation requires the generation of random variables from known statistical distributions. Hahn and Shapiro (*21*) give procedures for generating variates from several common distributions. Of special interest in this study are the statistical distributions for modulus of elasticity (E) of various laminating grades of lumber and tensile strength of end joints. Two frequently used theoretical distributions in these types of applications are the Weibull and the log-normal. Pierce (*33*) and Larsen (*23*) recommend the use of the three-parameter Weibull when dealing with lumber mechanical property data. Woeste et al. (*42*) reached similar conclusions specifically for sets of E data.

The three-parameter Weibull distribution is bounded on the left by location parameter μ. The density function is given by:

$$f(x;\ \eta,\ \sigma,\ \mu) = \left(\frac{\eta}{\sigma}\right)\left(\frac{x-\mu}{\sigma}\right)^{\eta-1} \exp\left\{\left(-\frac{x-\mu}{\sigma}\right)^{\eta}\right\} \qquad [5]$$

$$x \geq \mu,\ -\infty < \mu < \infty,\ \sigma > 0,\ \eta > 0,$$

$$0 \text{ elsewhere}$$

where

σ = scale parameter
η = shape parameter
μ = location parameter

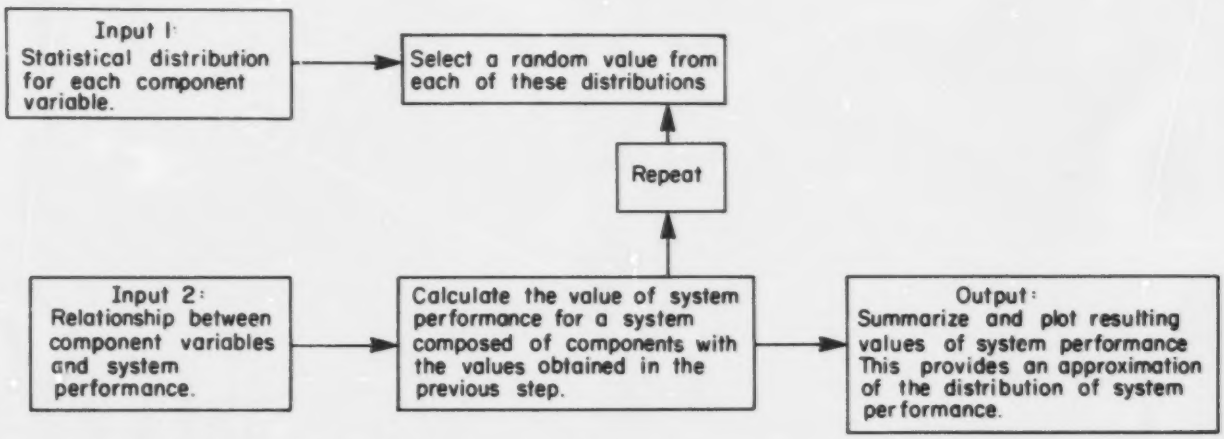
Input 1:
Statistical distribution for each component variable.
Select a random value from each of these distributions
Repeat
Input 2:
Relationship between component variables and system performance.
Calculate the value of system performance for a system composed of components with the values obtained in the previous step.
Output:
Summarize and plot resulting values of system performance This provides an approximation of the distribution of system performance.

Figure 3.—Flow chart of the Monte Carlo simulation method (25). (ML85 5222)

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Model Development

The behavior of any structure subjected to loads is dependent on the properties of its constituent elements. In the case of timber, the engineering properties of the structural elements are highly variable and behavior is difficult to predict. For this reason, a great deal of research has been targeted at finding new ways to determine the strength characteristics of heavy timber members. This section discusses a computer simulation model to predict the performance of structural glued-laminated timber beams under various loading conditions.

General Approach

The computer model developed here uses a statistical approach to beam strength prediction. Since the strength of actual lumber grades is modeled, no strength-reduction factors are necessary, as required by the clear wood adjustment approach.

One method of estimating the statistical distribution of glulam beam strength would be to initiate a large-scale destructive testing program. An appropriate statistical distribution could then be fitted to the data from which design stress levels could be established. Assuming that the sample size was sufficiently large and representative of the population, this approach would yield accurate results. However, the cost associated with a testing program of this magnitude would be prohibitive.

A computer model eliminates part of the need for large-scale destructive testing. The model of this study uses a Monte Carlo simulation technique to assemble a large number of beams in the computer and compute their bending strengths. In this manner, any beam size or layup can be easily analyzed.

The model is based on the observation that glulam beams behave elastically to first failure and that most bending failures of glulam beams initiate in the tension zone. If failure is assumed to initiate in the tension zone, the ultimate moment carrying capacity of the beam can be predicted with reasonable accuracy if the tensile strength and stiffness of each lamination is known. The ultimate moment is calculated by the transformed section method, which is used to analyze the elastic behavior of beams comprised of two or more materials with varying properties.

A brief description of the Monte Carlo scheme used in this model follows: Imaginary beams are built in the computer in the same manner that actual beams are assembled in a laminating plant. Laminations are selected according to grade requirements specified by the beam layup. One beam length lamination is made up of several pieces of laminating lumber connected by end joints. Each of these lamination segments has an associated modulus of elasticity (E), tensile strength, and length. All of these properties are random variables and must be generated from appropriate distributions. As previously mentioned, E and tensile strength are used in the transformed section analysis. The length of each piece of lumber must be included since it dictates the number and location of end joints in the beam. The tensile strength of end joints must be included in the model since tensile failures can also occur at an end joint. After the beams have been assembled, the "first failure" point in each beam is located and the corresponding ultimate moment is recorded. From this ultimate moment, an apparent modulus of rupture can be calculated from the usual flexural formula by assuming a homogeneous beam cross section. Finally, a theoretical statistical distribution is fitted to the modulus of rupture data for the assembled beams.

Monte Carlo simulation utilizes a number of component variables to predict system performance. The component variables used in this simulation are listed as follows:

1. Modulus of elasticity, E
2. Tensile strength of laminates, TL
3. Length of laminates, L
4. Tensile strength of end joints, TJ.

Some of these variables are statistically correlated. For example, E and TL are positively correlated and must be generated in pairs. The following sections discuss the statistical modeling of each component variable.

Modeling of Laminate Modulus of Elasticity and Tensile Strength

It is well known that for lumber, tensile strength parallel to grain is generally positively correlated with modulus of elasticity (e.g., *19*). For this reason, E and TL must be generated in pairs. Woeste et al. (*42*) outlined a procedure whereby a random selection of E from an appropriate distribution is followed by generation of a companion TL value from a regression equation relating TL to E. The same procedure was used here to generate E-TL pairs. Before the procedure is discussed in detail, the data used in this study will be described.

Pairs of E and TL data were obtained from a study that evaluated three U.S. laminating grades: 301A, L1, and L2 Douglas-fir (*31*). Grade 301A was a special tension lamination grade similar to the current grade 302-24 (*2*); L1 and L2 are commonly used U.S. Douglas-fir laminating grades. Within each of these grades, two levels of quality were sampled. One level was to represent a typical random sampling of the grade and the other was to represent lowline or near-minimum quality. The lowline data were chosen to contain the maximum-sized strength-reducing characteristic for the grades of interest. The raw material was nominal 2- by 6-inch by 16-foot Coast Region Douglas-fir.

Modulus of elasticity data for laminating grade L3 were obtained from a report by Wolfe and Moody (*43*). The corresponding tensile strength values for this lumber were not modeled, since L3 laminating stock is only used in low-stress areas in high-grade beams. For such high-grade beams, bending failures only rarely initiate in the L3 material. All of the modulus of elasticity (E) values were measured using a flatwise vibration technique.

Distribution of the E values is shown in figure 4.

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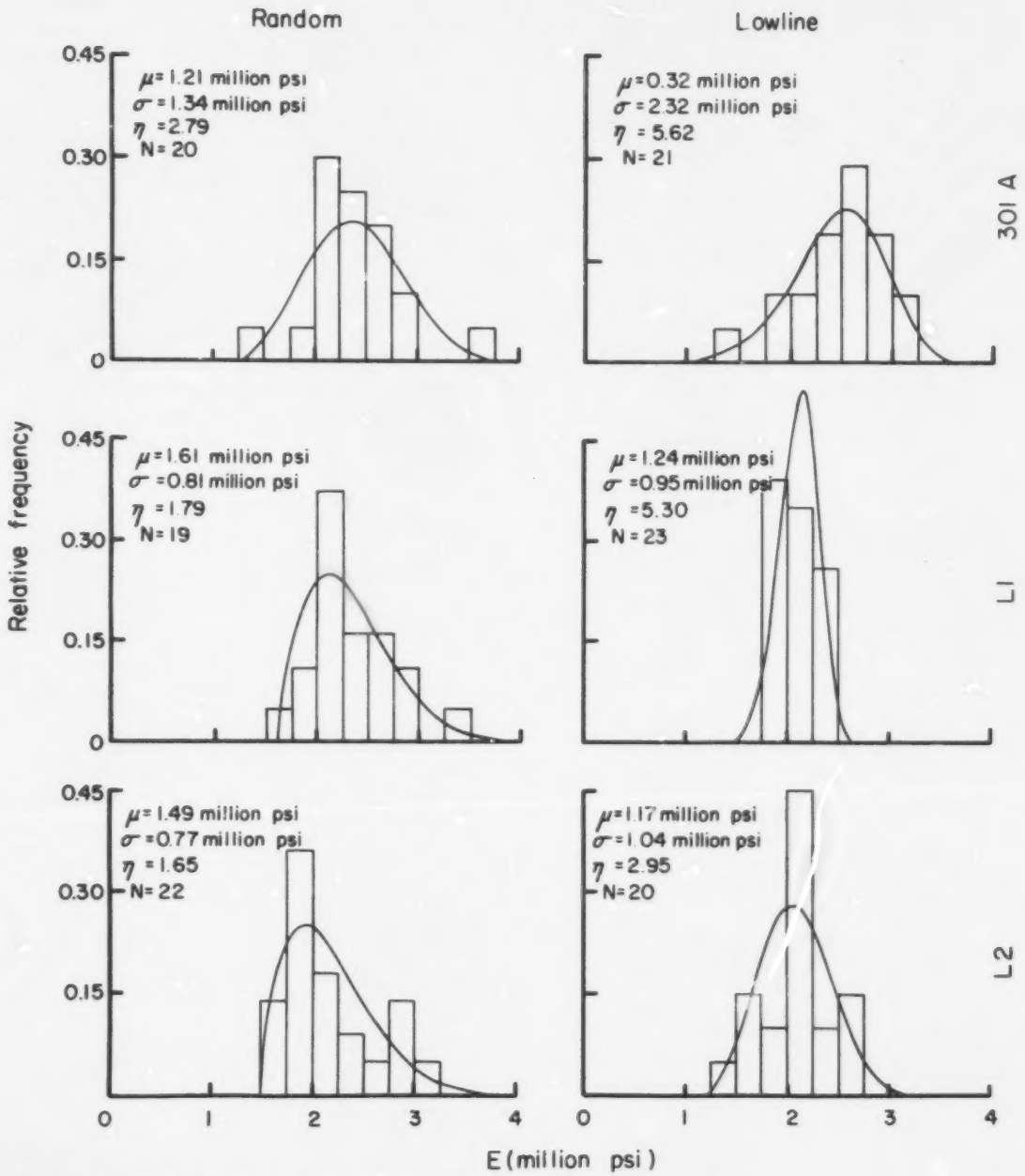

Figure 4.—Histograms of actual long span modulus of elasticity (E) data for 2- by 6-inch Douglas-fir special laminating grade 301A and laminating grades L1 and L2 (random and lowline). The three-parameter Weibull density function was fitted to the data, and the resulting curves coincide with the histograms. The lowline specimens were chosen to contain a near-maximum allowable strength-reducing characteristic for the grade (ML85 5226)

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The procedure used to model and subsequently generate compatible sets of strength and E values is described next. The analysis is summarized in three main steps.

1. For reasons given in the background information, the E data were fitted by the three-parameter Weibull distribution. The Weibull parameters were estimated numerically using the method of maximum likelihood (*38*). Figure 4 shows histograms of the three sets of normal and lowline E data with the corresponding probability density curves.

   Normally, a goodness-of-fit test would be conducted to evaluate how well the estimated density curves described the variation of the E data. However, since the sample sizes were on the order of 20, formal statistical tests will not generally discriminate between one distribution and another. Therefore, a visual appraisal was used to evaluate the data fit. In all cases, the distribution seemed to fit the data well.

2. For each of the six groups, scattergrams of tensile strength (Y) versus modulus of elasticity (X) were constructed. A weighted least squares regression analysis was then performed using a model of the form

$$Y = \beta_1 X + \beta_0 + \varepsilon \qquad [6]$$

   with the variance of ε equal to a constant K times the independent variable X. This variation in ε was chosen because tensile data for lumber appear to have residual function which varies with E (*25,42*). The parameters β_1, β_0, and K were estimated by b_1, b_0, and K as follows:

$$b_1 = \frac{\Sigma 1/X \, \Sigma Y - n \, \Sigma Y/X}{\Sigma 1/X \, \Sigma X - n^2} \qquad [7]$$

$$b_0 = \frac{\bar{X} \, \Sigma Y/X - \Sigma Y}{\bar{X} \, \Sigma 1/X - n} \qquad [8]$$

$$K = \frac{b_1^2 S_x^2 (1 - r^2)}{\bar{X} \, r^2} \qquad [9]$$

   where r is the estimated linear correlation coefficient, S_x is the estimated variance of X, and the summation over $i = 1, \ldots n$ is implied (*42*).

   Scattergrams of actual E-TL pairs with overlays of the regression lines exhibited a lack of fit near the lower boundary curve. To compensate for this lack of fit, Woeste et al. (*42*) found that a logarithmic transformation on the dependent variable, tensile strength, will greatly improve the relationship. Hence, the new regression model is given by

$$\ln (Y) = \beta_1 X + \beta_0 + \varepsilon \qquad [10]$$

   where the variance of ε is K times X, and β_0, β_1, and K are estimated as before with the exception that ln (Y) replaces Y.

   Figure 5 shows the plots of the transformed regression lines along with the 99 percent boundaries overlayed on scattergrams of the actual data. These models displayed no obvious lack of fit and, therefore, were used to simulate subsequent tensile strength values. (The logarithmic transformation is also desirable in that the probability of simulating values of near zero strength is very low, which is in agreement with actual experience.)

3. The final step was to generate values of tensile strength (TL) and compare them with the actual TL data. Corresponding values of E and TL were generated by the following procedure. First, a random value of E was generated from the appropriate three-parameter Weibull distribution. Then, a random residual, ε, defined by the regression model was added to the value of $\beta_1 E + \beta_0$. The inverse of the logarithmic transformation of the weighted least squares regression equation produces a random value of TL. The appropriate equation for this simulation is given by:

$$TL = e^{(\beta_1 E + \beta_0 + \varepsilon)} \qquad [11]$$

   Figure 6 shows histograms of the actual TL data along with the simulated values. The sample sizes of the simulated and actual data were on the order of 2,000 and 20, respectively. Again, a visual appraisal of goodness of fit was dictated by the small sample sizes involved. The question was asked, "Could the actual data be a sample from the simulated population?" In all six cases, there did not appear to be any significant lack of fit.

   The three-step procedure just described was used to generate E-TL pairs used in the prediction model for beam strength. It is important to note that the accuracy of any Monte Carlo simulation is partly contingent on the accuracy of the generated component variables. Therefore, it would be desirable to have a larger data base of E-TL pairs in order to obtain better estimates of the corresponding model parameters. Since no other data were available for 2- by 6-inch Douglas-fir laminating grades, the model parameters based on sample sizes of 20 were used to generate subsequent values of E and TL in the Monte Carlo simulation.

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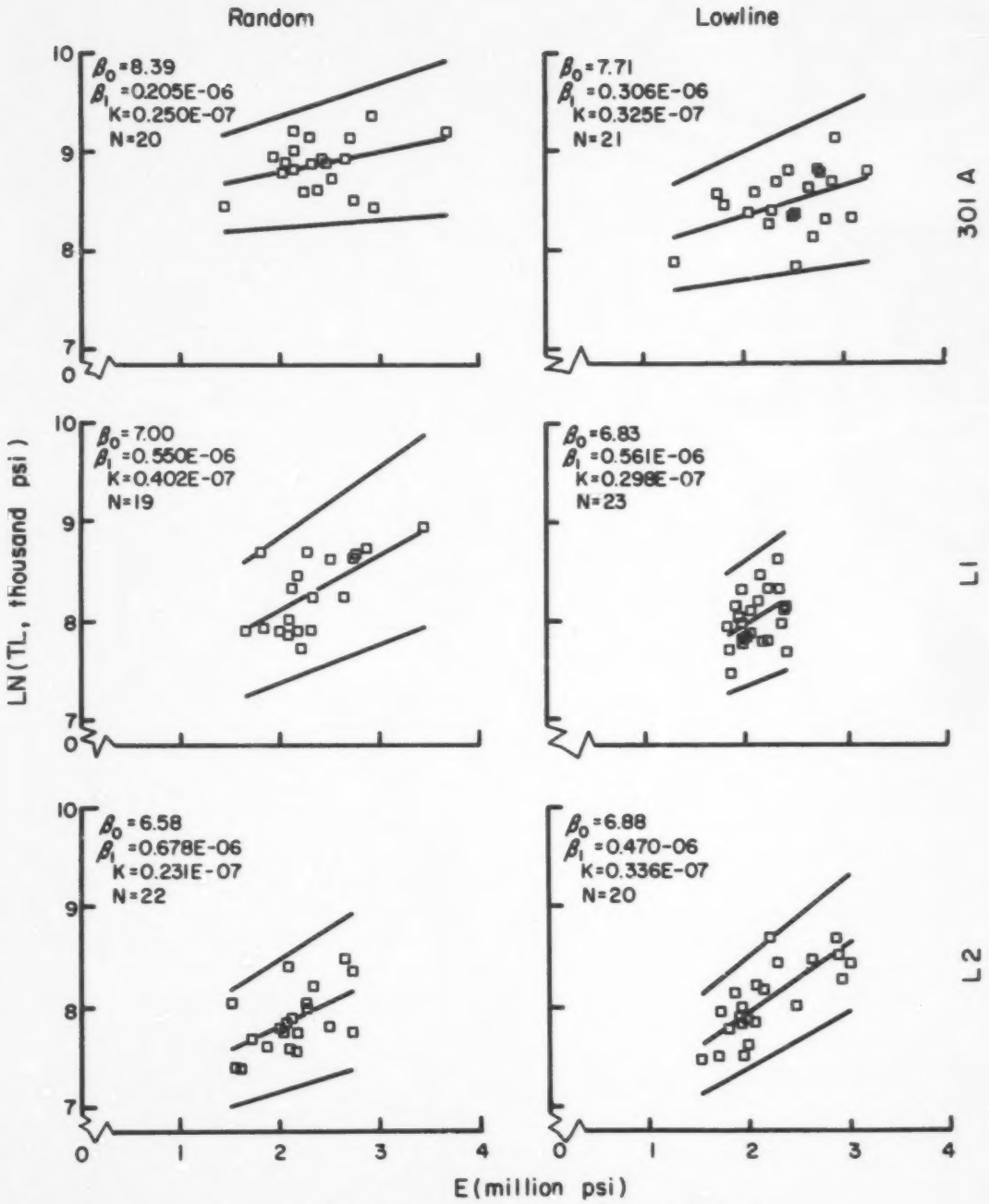

Figure 5.—Scattergram of the actual modulus of elasticity (E)-tensile strength (TL) pairs for 2- by 6-inch Douglas-fir special laminating grade 301A and laminating grades L1 and L2 (random and lowline). Overlays of the weighted least squares regression line and curves which bound 99 percent of the residuals are included. A logarithmic transformation was performed on the dependent variable, TL. The regression model appears to fit the data well. (ML85 5227)

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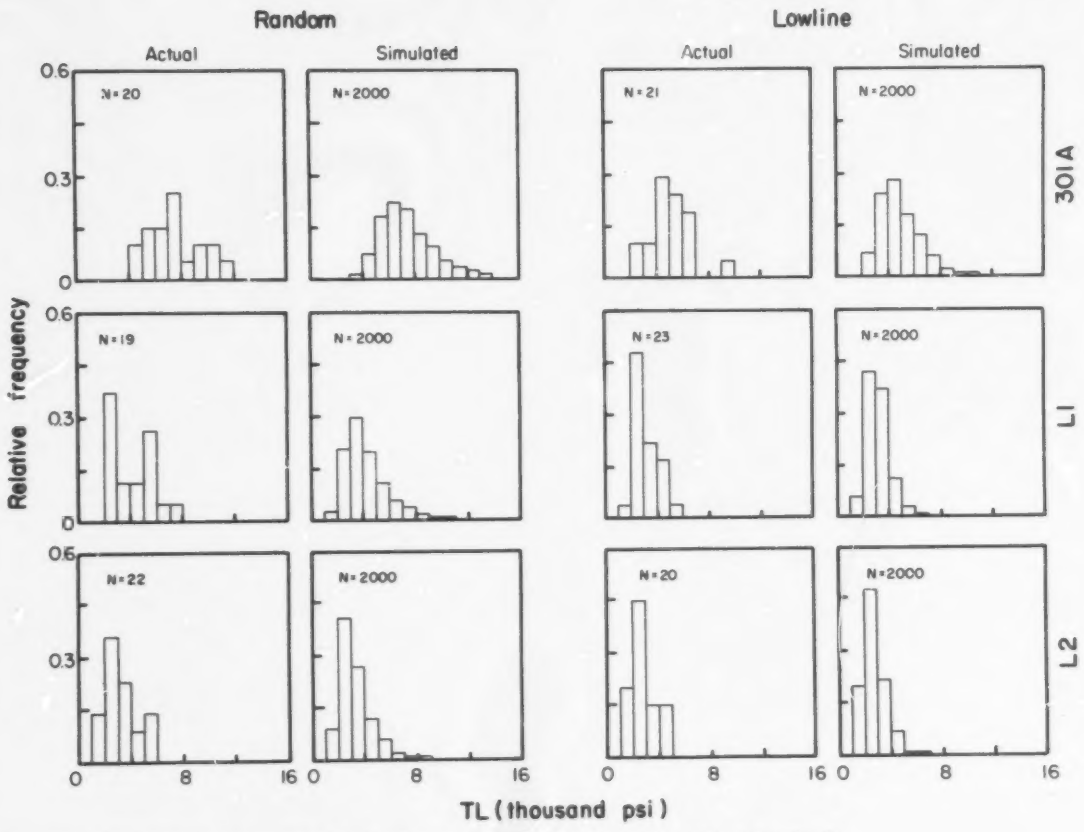

Figure 6.—Histograms for the actual and simulated tensile strength (TL) data for 2- by 6-inch Douglas-fir special laminating grade 301A and laminating grades L1 and L2 (random and lowline). Based on visual inspection, the simulated data for lowline closely mimic the data, whereas the simulated data for random only somewhat mimic the actual data. (ML85 5228)

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Modeling of End Joint Tensile Strength

Tests have shown that failure of a glulam beam may also initiate at an end joint (e.g., *27*). For this reason, end joints must be included in a computer model of beam strength. The end joint data used in this study were from 128 Douglas-fir tension tests made available by the American Institute of Timber Construction (AITC). Three end joint configurations were tested: horizontal finger joints, vertical finger joints, and scarf joints.

Although a small number of the end joint specimens had been edge-surfaced down to the usual finished Douglas-fir beam width of 5-1/8 inches, the majority had not. Yet, data from edge-surfaced end joints were required to estimate the necessary distribution parameters used in the beam strength model, since all joints are edge-surfaced in the manufacturing process for structural glulam timber. To account for this, a multiple linear regression model employing "dummy variables" was developed to remove the effects of edge-surfacing as well as the type of end joint. A complete discussion of the use of dummy variables in multiple regression is given by Draper and Smith (*15*), while a detailed description of the entire end joint data expansion procedure is given by Bender (*8*).

The three-parameter Weibull distribution was chosen to model the tensile strength of the end joints. The Weibull parameters were again estimated numerically for each type of joint using the model of maximum likelihood (*38*). Three-parameter Weibull density functions were then overlayed on histograms of the expanded data sets. Visual inspection of the distributions indicated a good fit.

In addition to this visual check, the Kolmogorov-Smirnov (K-S) test was used as a test for goodness of fit. The basic procedure of the K-S test involves the comparison between the experimental cumulative frequency and the assumed theoretical distribution function. If the discrepancy is large, the assumed model is rejected. The K-S test indicated an excellent fit. None of the three-parameter Weibull functions was rejected at the 20 percent level of significance (the higher the level, the easier to reject). The K-S test critical values are listed in table 1 and they are valid for a nonparametric test where the distribution parameters are specified. Critical values of the K-S test applicable to the three-parameter Weibull are unknown. According to Crutcher (*14*), if the critical value is exceeded by the test statistic, the null hypothesis is rejected with considerable confidence. This means that for a selected critical level of significance, say 0.2, the actual level of significance will be smaller. The estimated Weibull parameters are given in table 1.

Modeling of Lumber Length

The length of the laminating lumber is important since it determines the location of end joints. The distribution of length depends primarily on the length of available laminating stock, minus end trim. The assumed range of lengths in production beams was based upon estimates by several laminators. Higher-quality tension laminations were assumed to be somewhat shorter in length due to additional trimming for upgrading. For the purposes of this study, length was assumed to follow a log-normal distribution. Assuming that the range of the lengths was equal to four standard deviations, the log-normal parameters were estimated. Estimates of the log-normal parameters for mean (λ) and variance (ξ) are given in table 2.

Table 1.—Estimated end joint tensile strength Weibull parameters and K-S values for the expanded Douglas-fir data sets (the hypothesized distribution is rejected if the computed value of the K-S statistic exceeds the critical value)

Type of joint	N	η	μ	σ	K-S	
					Computed	Critical[1]
		Lb/in.^{2}				
Horizontal	128	3.550	3,350	3,810	0.057	0.095
Vertical	128	3.550	2,890	3,810	0.059	0.095
Scarf	128	3.550	3,080	3,810	0.057	0.095

[1]Critical K-S value at 20 percent level of significance.

Table 2.—Estimates of average length and range of lengths for 2- by 6-inch Douglas-fir laminating lumber, along with the associated log-normal parameters

	Mean	Range	λ	ξ
	------- *Ft* -------			
Lumber for tension laminations	10	6-14	2.283	0.198
All other lumber	12	8-16	2.471	0.166

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Transformed Section Analysis

The statistical modeling of the random variables (E, TL, L, TJ) makes it possible to generate appropriate synthetic values for use in the Monte Carlo simulation. These component random variables combine to form a strength distribution for glulam beams. The functional relationship used to combine these variables to arrive at estimates of beam performance involves a transformed section type of analysis.

Brown and Suddarth (*13*) developed a generalized computer program which performs the necessary calculations for a transformed section analysis. This program computes the maximum allowable moment for the i-th lamination, denoted m_i, by the following relationship:

$$m_i = \frac{E_s}{E_i}\left(\frac{I_s F_i}{C_i}\right) \qquad [12]$$

where

E_s = modulus of elasticity of the standard material
E_i = modulus of elasticity of the i-th lamination
F_i = allowable stress for the i-th lamination
I_s = moment of inertia of the transformed section
N = number of laminations
C_i = distance between the neutral axis of the transformed section and the extreme fiber of the i-th lamination

The maximum moment carrying capacity of the glulam beam is then determined by the minimum value of m_i.

Portions of the Brown-Suddarth (*13*) computer program were used in this study to perform the transformed section calculations. The major change in the program concerned the selection of a suitable value of C_i. As previously mentioned, C_i is the distance from the neutral axis of the transformed section to the extreme fiber of the i-th lamination. Although C_i is usually measured to the outer edge of the i-th lamination, for purposes of this study C_i was measured to the center of the i-th lamination. The reason is that the tensile strength values simulated in this study were derived from test specimens loaded in pure tension. As a result, the tensile stresses were uniformly distributed. The actual stresses in the tension laminations of a glulam beam in bending vary linearly. To equate the two stress distributions, C_i was measured to the center of the i-th lamination. In this manner, the average tensile stress in an actual tension lamination in a beam would be equal to the magnitude of the uniform stress distribution, which is the approximate state of stress of a tensile-tested lamination. This makes a difference in estimating the strength of shallow beams, but is of negligible effect for deep beams.

Summary of Beam Strength Model

This computer model uses Monte Carlo simulation to assemble glulam beams in the computer. For each of these beams the gross modulus of elasticity, ultimate moment, apparent modulus of rupture, failure location, and failure mode are recorded. The failure location is measured in inches using one end of the beam as a reference point. Failure mode is used to indicate whether an end joint is the cause of failure.

The following steps provide a summary of the simulation procedure for a single beam. These steps are repeated according to the desired sample size:

1. Lumber of randomly selected length, modulus of elasticity, and tensile strength are dealt into the bottom layer of the beam until the beam length requirements have been satisfied. Each subsequent layer is generated according to the grade specifications of the beam.

2. A random end joint tensile strength, drawn from the appropriate distribution, is assigned wherever two laminates meet end-to-end. End joints are not allowed to occur within 6 inches of each other in adjacent laminations in the tension zone as specified by PS-56-73 (*3*).

3. Steps 1 and 2 are repeated until the entire beam has been assembled. All of the random strengths and moduli of elasticity, E, are recorded in arrays, along with the location of each end joint.

4. A transformed section analysis is repeated across the entire beam cross section at a specified increment of beam length. In each case, tensile strength and E are used to calculate the ultimate moment. Then the ultimate moment, gross modulus of elasticity, failure location, and failure mode are stored in an array.

5. A transformed section analysis is performed at each end joint location. End joint tensile strength and E are used to calculate the ultimate moment. The end joint E is taken to be the average E of the two connecting laminations.

6. The minimum value of the ultimate moments determined in steps 4 and 5 is recorded. This value defines the ultimate moment carrying capacity for the assembled glulam beam.

7. The apparent modulus of rupture is calculated by assuming a homogeneous beam cross section.

8. The ultimate moment carrying capacity of the beam and the associated modulus of rupture, gross modulus of elasticity, failure location, and failure mode are recorded.

Failure is assumed to occur when the tensile strength parallel to the grain of a lamination is exceeded, with the stress for each lamination being calculated at the center of the lamination. This is referred to as "first failure." Gradual-type failures which result in redistribution of stresses are not predicted by this model.

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Summary of Fire Endurance Prediction Model

A fire endurance prediction model was developed by making minor refinements in the beam strength model. The fire endurance of glulam beams is measured by the time to failure (TTF), where TTF is defined as the length of time that the beam will support its design load when subjected to intense fire conditions. The fire endurance model can be used to predict the distribution of TTF for any glulam beam of interest. Fire is simulated by removing the char layer from the beam cross section. The thickness of the char layer R is given by

$$R = \beta t + \delta \qquad [13]$$

where

β = char rate
t = fire exposure time
δ = finite thickness of residual wood which is weakened by the elevated temperature and moisture

Two of the assumptions of this model are that char rate β and residual thickness δ remain constant. These two assumptions have received considerable experimental support (e.g., *22,24,30,34,39,40*). Another assumption is that the unit tensile strength and E properties of individual laminations remain constant as the cross section is reduced.

As previously mentioned, lateral torsional buckling is an important consideration in a fire endurance model for beams. Equation [4] was used as a check for lateral torsional buckling. For the purposes of this report, the fire-exposed beams were assumed to be uniformly loaded. Hence, the constant m from equation [4] was assigned a value of 28.0. Additional values of m are given by Pettersson (*32*) for other types of loads.

The following steps summarize the simulation procedure of the fire endurance model for a single beam. The first three steps involving beam assemblage are identical to those of the beam strength model. The other steps represent modifications to the beam strength model. These steps are repeated for each beam in the simulation:

1,2,3. Beam assemblage.

4. Time is set equal to zero.

5. The full design load in bending is applied to the beam as a uniform load.

6. A repeated transformed section analysis is performed across the entire length of the beam at a specified increment. For this study the increment was chosen as 6 inches. In each case, the applied moment and lamination E are used to calculate the stresses in the laminations of interest.

7. A repeated transformed section analysis is performed at each end joint location. End joint E is taken to be the average E of the two connecting laminations. The applied moment and the end joint E values are used to calculate the stresses in the laminations of interest.

8. The computed stresses of steps 6 and 7 are compared to the corresponding tensile strength values. If the tensile strength is exceeded, failure occurs and TTF is recorded.

9. The critical moment permitted by lateral torsional buckling is calculated. If the critical moment is exceeded by the applied moment, failure occurs and TTF is recorded.

10. Time is increased by 1 minute and the corresponding char thickness is removed from the cross section.

11. Steps 6 through 10 are repeated until beam failure is detected. The program for this analysis is contained in Appendix A.

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Preliminary Room Temperature Beam Strength Results

Actual beam strength data were obtained from a study on the bending strength of shallow glulam beams (*27*). Of 120 beams tested, 60 were constructed from visually graded Douglas-fir lumber. The 60 Douglas-fir glulam beams were used to calibrate the beam strength model. The three beam sizes chosen were 4, 8, and 10 laminations. The layup for each beam type is shown in figure 7. Half of the Douglas-fir beams had specially graded tension laminations referred to as 302-24, and the other half had tension laminations of grade L1. The 302-24 and L1 lumber used as tension laminations were chosen to contain a strength-reducing characteristic close to the maximum allowed for the grade, and were referred to as "lowline" lumber. In addition, the maximum observed strength-reducing characteristic was positioned in the maximum-moment region of the beam.

The beams were tested according to ASTM D 198 (*4*). Two-point loading was used. Spans were 9.5, 19.0, and 24.0 feet for the 4-, 8-, and 10-lamination beams, respectively. Similarly, the distance between load heads was 2.0, 4.0, anld 5.0 feet, respectively.

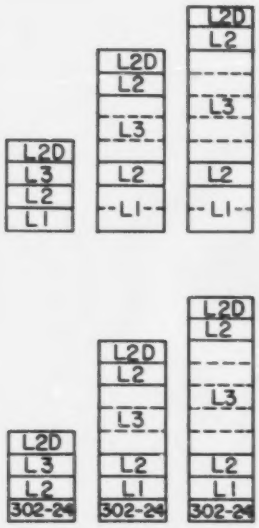

Figure 7.—Layups of the six beam groups used in the calibration of the beam strength model. Half of the beams had specially graded 302-24 lowline tension laminations and the other half had L1 lowline tension laminations. All other laminations were chosen to be a random sampling of the grade. The lamination grades are listed in order of increasing severity of defects as follows: 302-24, L1, L2D, L2, L3. (ML85 5225)

The shallow glulam beam study also included individual modulus of elasticity data for the lowline tension laminations. These data were fitted by a three-parameter Weibull distribution which was used to subsequently generate values of E in the simulation model. The report also included average E values for the other laminating grades as well as the average finger joint strength. These average values were used to adjust the Weibull scale and location parameters which were previously determined. A summary of the input parameters for the beam strength simulation model is given in table 3.

Some of the test beams exhibited a gradual type of failure with cracking or splintering of the tension lamination, accompanied by varying amounts of drop in the test machine load (*27*). For purposes of this study, the load which caused first failure for these beams was used in the model calibration. The beam strength model was run for all six beam groups. The actual and predicted values of bending strength are given in table 4 and are graphically portrayed in figure 8.

Even though the sample sizes for the beam test data were small, there appeared to be a major source of error in the beam strength model. In all cases, the beam strength predictions were quite low. The predicted coefficients of variation were one-half to one-third of the variation observed. The reason for most of the differences between these preliminary predictions and the beam test results is that no provisions were included in the model to adjust from the single lamination tensile strength data input to the full-size glulam beam bending strength predictions. Data show that difference to be significant (e.g., *12*). Two main phenomena are thought to be responsible for the significant difference between single lamination tensile strength data and full-size glulam timber bending strength data. One of these phenomena is known as the "laminating effect," which represents the load sharing between adjacent laminations. The other is known as the "length effect," and is due to the differences between the test span lengths for the tensile strength data input and the beam bending strength data used for calibration. Both the laminating and length effects are important, but we decided to modify the model considering the length effect only.

Effect of Length on Tensile Strength

As mentioned in the statistical modeling of the laminations, the tensile strength regression parameters were estimated from test data on 16-foot-long specimens. The specimens were gripped for a distance of 2 feet on each end; therefore, the length actually subjected to the tensile load was 12 feet. However, the lengths of the laminations in the most critically stressed portions of the beams were considerably shorter than 12 feet. To account for this situation. the tensile strength values need to be adjusted.

A specimen loaded in tension will fail at the weakest point, or in the case of lumber, it will fail at the most severe strength-reducing characteristic. Hence, the longer the specimen, the higher the likelihood of encountering a severe strength-reducing characteristic. This problem can be analyzed by equating a long piece of lumber to a simple series system.

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Table 3.—Input parameters used to calibrate the beam strength-prediction model (Weibull parameters for modulus of elasticity data, regression parameters which relate lamination tensile strength to modulus of elasticity, log-normal parameters used to define the length of the lumber comprising the laminations, and Weibull parameters for the tensile strength of vertical finger joints)

Lumber grade	Weibull parameters			Regression parameters			Length parameters	
	σ	η	μ	b_o	b_1	K	λ	ξ
	Modulus of elasticity							
	10^6 lb/in.^{2}		*10^6 lb/in.^{2}*					
[1]302.24	1.08	4.49	1.49	7.71	0.306E-06	0.325E-07	2.283	0.198
[1]L1	1.02	3.38	1.35	6.83	0.561E-06	0.298E-07	2.283	0.198
L2D	0.71	1.65	1.38	6.58	0.678E-06	0.231E-07	2.471	0.166
L2	0.61	1.65	1.18	6.58	0.678E-06	0.231E-07	2.471	0.166
L3	0.83	2.60	0.94	6.88	0.470E-06	0.336E-07	2.471	0.166
	Tensile strength							
	10^3 lb/in.^{2}		*10^3 lb/in.^{2}*					
Vertical finger end joints	3.36	3.55	2.54	- -	- -	- -	- -	- -

[1] Specimens were chosen to contain the maximum allowable strength reducing characteristic for the grade and referred to as "lowline" material.

Table 4.—Estimated Weibull parameters for the six sets of lamination tensile strength data used in the strength-modulus of elasticity regression model

Lumber grade	Sample size N	Tensile strength Weibull parameters		
		η	σ	μ
			10^3 lb/in.^{2}	
301A	20	1.74	3.66	4.20
[1]301A	21	1.95	3.24	2.10
L1	19	1.45	1.99	2.23
[1]L1	23	1.75	1.67	1.65
L2	22	1.10	1.70	1.76
[1]L2	20	1.11	1.16	1.61

[1]Lowline specimens.

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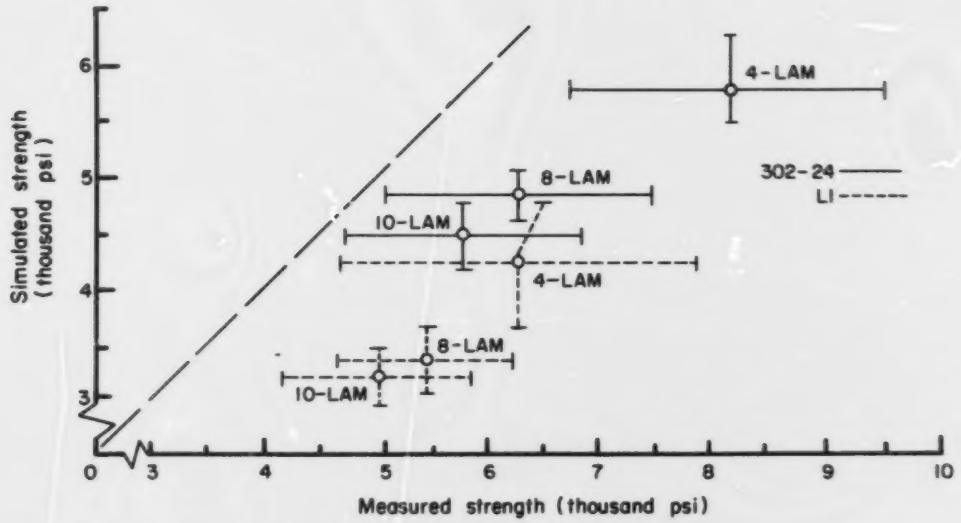

Figure 8.—Predicted beam strength means and variation (COV) (using the unrefined simulation model) vs. measured values. Tension laminations in the 4-, 8-, and 10-lamination beams are either L-1 or 302-24. (Data from table 4.) (ML85 5223)

If the components of a system are connected in series, failure of any component constitutes failure of the system. Therefore, the reliability of the system is dependent on the number of the components and their respective reliability functions. This concept is expressed mathematically as follows:

$$R_N(T) = [R_1(T)]^N \qquad [14]$$

where

$R_N(T)$ = reliability function of the system
$R_1(T)$ = reliability function of the component
T = random variable of interest
N = number of components

In the case of lumber, $R_N(T)$ is the reliability function of the long pieces and T represents tensile strength. $R_1(T)$ is the reliability function of the short pieces where N is determined by the ratio of the lengths of the long pieces to those of the short pieces.

To transform the tensile strength of a long specimen to that of a short specimen, the two reliability functions are set equal to each other. For example, a value T corresponding to the fifth percentile from the long specimen distribution would be transformed to a fifth percentile value T′ of the short specimen distribution. The transformation is carried out by solving the following equation for T′:

$$R_N(T) = [R_N(T')]^{1/N} \qquad [15]$$

Assuming that the tensile strength of the long pieces follows a three-parameter Weibull distribution, the transformation equation which can be used to convert a known long value of T to the appropriate short value T′ is given by:

$$T' = T(N)^{1/\eta} + \mu[1 - (N)^{1/\eta}] \qquad [16]$$

where

N = ratio of lengths of long pieces to short pieces
η = Weibull shape parameter
μ = Weibull location parameter

It is interesting to note that the problem of amount of material exposed to maximum moment or volume experienced in this research is the same problem identified and solved by Bohannan (*10,11*). Bohannan's solution was based on the Weibull "weakest link theory," and beam strength was obtained by integrating a material function over the area of the beam defined by its depth and length. The parameters of the material function were evaluated from test data on 2,056 clear, straight-grained Douglas-fir beams.

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For the research described in this paper, we chose to solve the problem of volume or stress exposure by a different approach, since we could not integrate over a region of lamination or slices of different laminating stress grades. However, with lamination tension data being available, it was thus possible to adjust the long test lengths to shorter lengths comparable to the laminated beam test configuration using the Weibull "weakest link theory." This procedure is almost identical to the integration procedure in that (1) most failures occur in the tension zone where the adjustments were made and (2) the individual lamination adjustment can be thought of as a numerical integration of the integral used by Bohannan (*10,11*). It should not be argued that the individual lamination adjustments made in this research are superior to the area integration of the material function.

Final Room Temperature Beam Strength Results

Adjustments were made in the preliminary model using the theory developed in the previous section. Predictions made with the modified model were then compared with the beam strength data.

To use the length effect transformation, it was necessary to obtain estimates of the Weibull parameters for the six sets of original tensile strength data from the E-TL analysis. The maximum likelihood estimates are given in table 4. The value of N in transformation equation [16] was computed by dividing the length of the original tensile specimens (12 ft) by the length of the maximum moment region of the test beams. The latter length was equal to the distance between the loading heads for each beam size. This varied from 2.0 to 4.0 to 5.0 feet and resulted in values of N equal to 6.0, 3.0, and 2.4 for the 4-, 8-, and 10-lamination beams, respectively. The tensile strength transformation equations were then incorporated into the beam strength-prediction model and the calibration procedure was repeated. The resulting beam strength predictions appear in table 6, and are compared more graphically in figure 9. The final version of the refined simulation computer model is contained in Appendix B.

The beam strength predictions for the 8-lam and 10-lam beams with 302-24 lowline tension laminations agreed with the test values almost exactly. The strength predictions for the 8-lam and 10-lam beams with L1 lowline tension laminations were 14 and 17 percent lower than the test values, respectively. The predicted strength values for the 4-lam beams were approximately 30 percent higher than the test values. The discrepancies between the predicted and actual strengths for the 4-lam beams are probably due to several faulty assumptions. For example, the tension laminations are assumed to be in pure tension; however, this assumption is less valid for shallow beams. A second reason for the discrepancies for the 4-lam beams is that shallow beams are more sensitive to sampling error. Due to the small sample sizes involved in the simulation, sampling error alone could account for the discrepancies. The predicted coefficients of variation were lower than those of the test data by varying degrees; however, the predictions were greatly improved over the original predictions given in table 5.

Table 5.—Actual and predicted beam strength values (the tension laminations were selected from "lowline" material)

Beam	Tension lam	Modulus of rupture					
		Predicted			Observed		
		Mean	COV	N	Mean	COV	N
		Lb/in.²	*Pct*		*Lb/in.²*	*Pct*	
4-lam	302-24	5,896	6.7	500	8,163	17.1	10
	L1	4,218	14.2	500	6,291	25.4	10
8-lam	302-24	4,839	4.8	500	6,294	19.0	10
	L1	3,350	9.2	500	5,465	14.3	10
10-lam	302-24	4,468	6.7	500	5,795	18.5	10
	L1	3,196	8.7	500	5,032	16.8	10

Table 6.—Actual and predicted beam strengths, coefficients of variation, and sample sizes from the refined beam strength model (the tension laminations were selected from "lowline" material)

Beam	Tension lam	Modulus of rupture					
		Predicted			Observed		
		Mean	COV	N	Mean	COV	N
		Lb/in.²	*Pct*		*Lb/in.²*	*Pct*	
4-lam	302-24	10,755	10.1	500	8,163	17.1	10
	L1	8,022	21.8	500	6,291	25.4	10
8-lam	302-24	6,439	11.0	500	6,294	19.0	10
	L1	4,698	13.8	500	5,465	14.3	10
10-lam	302-24	5,803	8.9	500	5,795	18.5	10
	L1	4,155	11.3	500	5,032	16.8	10

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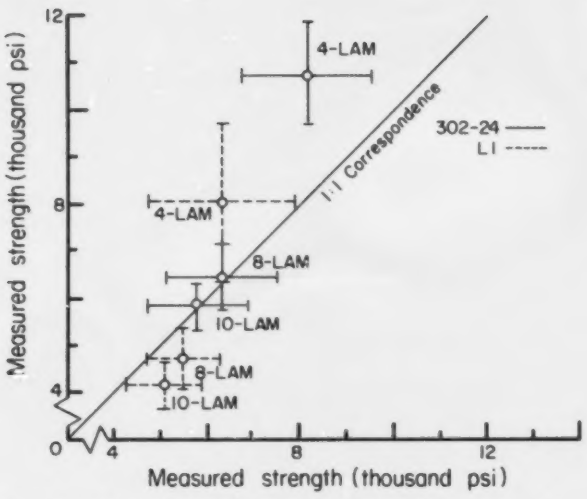

Figure 9.—Predicted beam strength means and variation (COV) (using the refined beam strength model) vs. measured values for 4-, 8-, and 10-lamination beams. Beams have either 302-24 or L-1 tension lamination. (Data from table 6.) (ML85 5224)

All factors considered, the beam strength simulation model reasonably predicted glulam beam strength. One cannot conclude that the model is either verified or discredited by the evidence gathered and analyzed. Several factors probably contributed to the discrepancies between predicted and observed results. The regression parameters used to generate lamination tensile strengths were estimated from sample sizes of only 20. Furthermore, all of the test specimens used to estimate the regression parameters were obtained from a single laminating plant and thus may not be representative of typical laminating grades. One final consideration is that the sample size of the test beams used in the calibration was small. The estimated variance of observed beam strength, and hence coefficient of variation, is subject to significant sampling error with a sample size of 10.

With the length effect adjustment, the predicted and actual beam test results agree as well as can be expected. Thus, further refinement of the model for the "laminating effect" was not pursued.

In short, the predictive ability of the model is promising but further validation by conducting bending experiments on beams designed for this purpose is required. Such effort is underway.

Fire Endurance Results

Owing to a lack of available fire endurance data, the fire endurance model (Appendix A) was run for a typical glulam beam size and the results were compared with conventional fire endurance estimates. A uniformly loaded 11-lamination Douglas-fir beam with a 302-24 tension lamination was chosen for investigation. Beam construction was assumed to be Douglas-fir combination 24F-V4 as specified by AITC 117-79 (*2*). The beams were assumed to be 5-1/8 inches wide, 16-1/2 inches deep, and 27 feet long.

The model was run for two cases. In the first case, the ratio k of allowable design stress to ultimate stress at room temperature was equal to 0.476 (i.e., 1/2.1) as specified by ASTM D 2915 (*5*). In the second case, k was arbitrarily chosen as 0.333 (i.e., 1/3). For both runs, char rate β and residual depth δ from equation [13] were assigned values of 1/40 inch per minlute and 0.2 inch, respectively. Also, three-sided fire exposure was assumed. Uniform loads of 572 and 400 pounds per linear foot were calculated for the stress ratios of 0.476 and 0.333. All other input parameters are given in table 3.

Before fire endurance could be predicted, the previously discussed lamination tensile strength transformation had to be modified due to the different loading condition. The room temperature beams were tested under two-point loading, which resulted in a constant moment section at the midspan. All of the simulated beam failures initiated in this constant moment section. Hence, the load span was used to calculate the value of N used in transformation equation [16]. On the other hand, fire-exposed beams are typically tested under a uniform load. The approach used for the fire-exposed beams was to define an effective length, 1*, to be used in place of the load span for the calculation of N in equation [16]. For the uniformly loaded beams, the effective length 1* was defined as:

$$1^* = L - 15d \qquad [17]$$

where L is the beam length and d is the beam depth. The relationship for effective length was derived from the room temperature beams under two-point loading.

The average time to failure (TTF) for k equal to 0.476 was 40.3 minutes with a coefficient of variation of 11.9 percent. The TTF was also estimated using a method derived by Lie (*24*). Lie's derivation is similar to that of Imaizumi (*22*) with the exception of three-sided fire exposure. The average predicted value of TTF using Lie's method was approximately 39 minutes. Similarly, fire endurance was predicted for k equal to 0.333. The average TTF predicted by our model was 53.1 minutes with a coefficient of variation of 8.9 percent. This also compared favorably with Lie's estimate of 54 minutes.

There are many practical applications of the fire endurance prediction model formulated in this report. The estimated distribution of TTF could be used in a second moment reliability analysis (*41*). With a second moment safety analysis, numerous design alternatives could be investigated. For example, the effect that changing laminating grades in beam combinations has on fire safety could be investigated. Furthermore, optimum beam geometries with respect to fire safety could be established.

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Summary and Conclusions

A computer simulation model was developed to predict the bending strength of glued-laminated beams (Appendix B). The model was then extended to predict the fire endurance of glulam beams (Appendix A). The beam strength model was calibrated and refined using actual beam test data on 4-, 8-, and 10-lamination Douglas-fir beams.

The model predicted the bending strength of 8- and 10-lamination beams with good accuracy (fig. 9); however, the strength predictions for the 4-lamination beams were considerably higher than the test values. As a result, the model appears to favor deep beam strength prediction. This requires further validation, however. Fire endurance also was predicted for 11-lamination Douglas-fir beams. The fire endurance predictions were in excellent agreement with predictions made from a method described by Lie (*24*).

In conclusion, the statistical approach outlined seems well suited for predictions of the strength and fire endurance of glulam beams. The simulation model was derived using data on 2- by 6-inch Douglas-fir laminating stock; however, the model can be easily adapted to predict the strength of other species as modulus of elasticity and tensile strength data are made available. Another feature of this model is that it is especially suited for parameter sensitivity studies. For example, the effect of lumber length (and hence the number of finger joints) on beam strength could be easily determined. In addition, the effect of grade combinations and beam geometries on fire endurance could be assessed. Finally, the fire endurance simulation model can be used, along with a second moment reliability analysis, to analyze glulam beams with respect to fire safety.

Further Research Needs

1. Verify a statistical length relationship for the tensile strength of laminating lumber.
2. Delineate the proportion of the influence on glulam beam strength prescribed by model parameters due to "length effect" and "laminating effect." How is each effect influenced by beam geometry, beam span, and number and quality of laminations?
3. Obtain additional information on the tensile strength of end joints to improve on the confidence of the existing data base.
4. Obtain additional data on E and tensile strength for laminating lumber.
5. Obtain information on the statistical distribution of the length of various grades of laminating lumber.
6. Obtain information on end joint stiffness.
7. Evaluate the beam depth limitations of the model reported herein.

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Appendix A
User's Guide and Program Listing of Fire Endurance Model

This program uses a Monte Carlo simulation scheme to predict the time to failure of fire-exposed glued-laminated beams under a uniform load. Standard fire exposure is simulated by artificially removing a char depth from the beam cross section until the applied load is equal to the ultimate load which the charred beam can support. The char depth is calculated by multiplying a constant char rate times the fire exposure time. An additional thickness of residual wood is then removed from the uncharred cross section to account for wood which is damaged by the elevated temperature and moisture content.

The input quantities are defined in the order that they are read into the computer program. The following is a guide for inputting these quantities.

Basic Parameters:

FORMAT (3I5, F10.5, D16.0, 3F10.2)

NLAMS	NINT	NBEAM	BASE	DSEED	LBEAM	XC	XXC

NLAMS = Number of laminations.
NINT = Number of tension laminations which are to be checked for failure.
NBEAM = Number of beams to be simulated.
BASE = Width of the beam.
DSEED = A double precision integer value in the exclusive range (1, 2147483647). This value is used to seed the random number-generating subroutines.
LBEAM = Length of beam in inches.
XC = Distance from the left end of the beam to the first point load, measured in inches.
XXC = Distance from the left end of the beam to the second point load, measured in inches.

Basic Parameters:

FORMAT (I5, 4F10.3)

NEXP	ULOAD	CRATE	TINC	RESID

NEXP = The number of sides which are exposed to fire (i.e., 3- or 4-sided exposure).
ULOAD = The uniform load applied to the beam in pounds per linear inch.
CRATE = Char rate in inches per minute.
TINC = Time increment used to calculate time to failure in minutes.
RESID = Finite distance into the residual wood damaged by the elevated temperature and moisture in inches.

Tensile Strength Transformation Parameters:

FORMAT (4F7.3, 4F9.2, F8.3)

SHAPE1	SHAPE2	SHAPE3	SHAPE4	ZLOC1	ZLOC2	ZLOC3	ZLOC4	FACTOR

SHAPE1 = Weibull shape parameter for the tensile strength data used in the regression model for E-TL pairs. This shape parameter should correspond to the lamination grade used in the bottom lamination of the glulam beam.
SHAPE2 = Shape parameter corresponding to the first lamination from the bottom of the beam.
SHAPE3 = Shape parameter corresponding to the second lamination from the bottom of the beam.
SHAPE4 = Shape parameter corresponding to the third lamination from the bottom of the beam.
ZLOC1 = Weibull location parameter for the tensile strength data used in the regression model of the E-TL pairs. This location parameter should correspond to the lamination grade used in the bottom lamination of the glulam beam. The location parameter is expressed in psi.
ZLOC2 = Location parameter corresponding to the first lamination from the bottom of the beam.
ZLOC3 = Location parameter corresponding to the second lamination from the bottom of the beam.
ZLOC4 = Location parameter corresponding to the third lamination from the bottom of the beam.
FACTOR = This value is equal to (12/load span in feet).

Modulus of Elasticity Weibull Parameters:

FORMAT (3E10.4)

MU	SIGMA	ETA

**Input as many cards as NLAMS

MU = Weibull location parameter for the laminate stiffness distribution. The location parameter is expressed in million psi.
SIGMA = Weibull scale parameter for the laminate stiffness distribution. The location parameter is expressed in million psi.
ETA = Weibull shape parameter for the laminate stiffness distribution.

Regression Parameters:

FORMAT (3E10.4)

B0	B1	KREG

**Input as many cards as NLAMS

B0 = Estimate of weighted least squares regression parameter b_0.
B1 = Estimate of weighted least squares regression parameter b_1.
KREG = Factor multiplied by the independent variable to obtain an estimate of the residual variance.

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Laminate Length Parameters:

FORMAT (2F10.3)

XI	TAU

**Input as many cards as NLAMS

XI = Estimate of the log-normal parameter corresponding to the expected value of the natural logarithm of the laminate length.

TAU = Estimate of the log-normal parameter corresponding to the expected value of the variance of the natural logarithm of the laminate length.

End Joint Tensile Strength Weibull Parameters:

FORMAT (3E10.4)

SIGJNT	ETAJNT	MUJNT

**Input as many cards as NLAMS

SIGJNT = Weibull scale parameter for the end joint tensile strength distribution. The scale parameter is expressed in thousand psi.

ETAJNT = Weibull shape parameter for the end joint tensile strength distribution.

MUJNT = Weibull location parameter for the end joint tensile strength distribution. The location parameter is expressed in thousand psi.

Laminate thickness:

FORMAT (1F10.5)

THICK

**Input as many cards as NLAMS

THICK = Laminate thickness in inches.

Example Problem

Input:

```
   4    2   10   5.12500      123476.D0      114.00      45.00     69.00
   3   45.000     0.025     1.000     0.200
 1.750  1.100  1.110  1.100  1650.00  1760.00  1610.00  1760.00  6.000
1.38     0.71     1.65
0.94     0.83     2.60
1.18     0.61     1.65
1.35     1.02     3.38
6.88     0.678E-06 0.231E-07
6.88     0.470E-06 0.336E-07
6.58     0.678E-06 0.231E-07
6.83     0.561E-06 0.298E-07
2.471    0.166
2.471    0.166
2.471    0.166
2.283    0.198
3.88     3.70     2.98
3.88     3.70     2.98
3.88     3.70     2.98
3.88     3.70     2.98
  1.50000
  1.50000
  1.50000
  1.50000
```

Output:

Beam No.	Gross MOE (psi)	Time to failure (min)	Depth (in.)	Width (in.)	Failure location (in.)	Lam No.	Mode*	LTB**
1	0.18011E+07	38.00	4.850	2.825	48.00	4	0	0
2	0.16398E+07	28.00	5.100	3.325	48.00	4	0	0
3	0.21533E+07	32.00	5.000	3.125	54.00	4	0	0
4	0.20390E+07	33.00	4.975	3.075	54.00	4	0	0
5	0.19670E+07	34.00	4.950	3.025	48.00	4	0	0
6	0.19510E+07	29.00	5.075	3.275	72.00	4	0	0
7	0.21701E+07	36.00	4.900	2.925	54.00	4	0	0
8	0.19337E+07	33.00	4.975	3.075	54.00	4	0	0
9	0.20552E+07	37.00	4.875	2.875	48.00	4	0	0
10	0.18758E+07	23.00	5.225	3.575	54.00	4	0	0

*MODE equals 0 or 1 if failure occurs at a laminate or finger joint, respectively.

**LTB equals 1 if lateral torsional buckling governs failure, and 0 if lateral torsional buckling does not govern failure.

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```
C*****************************************************************************
C*                                                                           *
C*                                                                           *
C*                    COMPUTER SIMULATION MODEL FOR                          *
C*                    PREDICTING THE FIRE ENDURANCE                          *
C*                      OF GLUED-LAMINATED BEAMS                             *
C*                                                                           *
C*                                                                           *
C*****************************************************************************
C
C
C     THIS PROGRAM USES A MONTE CARLO SIMULATION SCHEME TO PREDICT THE
C     TIME TO FAILURE OF FIRE EXPOSED GLUED-LAMINATED BEAMS UNDER A
C     UNIFORM LOAD.  STANDARD FIRE EXPOSURE IS SIMULATED BY ARTIFICIALLY
C     REMOVING A CHAR DEPTH FROM THE BEAM CROSS SECTION UNTIL THE APPLIED
C     STRESS IS EQUAL TO THE ULTIMATE STRENGTH OF THE CHARRED BEAM.  THE
C     CHAR DEPTH IS CALCULATED BY MULTIPLYING A CONSTANT CHAR RATE TIMES
C     FIRE EXPOSURE TIME.  AN ADDITIONAL THICKNESS OF RESIDUAL WOOD IS
C     THEN REMOVED FROM THE UNCHARRED CROSS SECTION TO ACCOUNT FOR WOOD
C     WHICH IS DAMAGED BY THE ELEVATED TEMPERATURE AND MOISTURE CONTENT.
C
C
C     THE VARIABLES ARE FIRST DIMENSIONED AND THEN ALL OF THE INPUT/
C     OUTPUT FORMAT STATEMENTS ARE GIVEN.
C
C
      DIMENSION ETA(30),SIGMA(30),B0(30),B1(30),XI(30),TAU(30),
     1 SIGJNT(30),ETAJNT(30),E(50,30),EE(30),TT(30)
     2 ,FJNT(50,30),T(50,30),R(10000),RR(10000),THICK(30),TTHICK(30)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
      DOUBLE PRECISION DSEED
      REAL MU(30),KREG(30),MUJNT(30),LBEAM,L(50,30),MNT,JNTLCN(50,30)
     1 ,IY,IX,IP,LCF,MCR
      INTEGER SIGNAL(50),FAIL2,FAIL3,N(30),FLVEL
    2 FORMAT(3E10.4)
    4 FORMAT(2F10.3)
    6 FORMAT(1X,'BEAM',5X,'GROSS',8X,'TIME',3X,'DEPTH',4X,'WIDTH',3X,
     1 'FAILURE',2X,'LAM',2X,'MODE',2X,'LTB'/2X,'NO.',6X,'MOE',10X,'TO',
     2 5X,'(IN)',5X,'(IN)',3X,'LOCATION',2X,'NO.'/10X,'(PSI)',7X,
     3 'FAILURE',19X,'(IN)'/23X,'(MIN)')
    8 FORMAT(I5,F14.5,F9.2,2F8.3,F9.2,3I5)
   10 FORMAT(F10.5)
   12 FORMAT(3I5,F10.5,D16.0,3F10.2)
   14 FORMAT(4F7.3,4F9.2,F8.3)
   16 FORMAT(I5,4F10.3)
C
C
C     THE INPUT VARIABLES DESCRIBED IN THE USER'S GUIDE ARE ENTERED NEXT.
C
C
```


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```
      READ(7,12) NLAMS,NINT,NBEAM,BASE,DSEED,LBEAM,XC,XXC
      READ(7,16) NEXP,ULOAD,CRATE,TINC,RESID
      READ(7,14) SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,ZLOC4,
     1           FACTOR
         DO 80 I=1,NLAMS
   80    READ(7,2) MU(I),SIGMA(I),ETA(I)
         DO 81 I=1,NLAMS
   81    READ(7,2) B0(I),B1(I),KREG(I)
         DO 82 I=1,NLAMS
   82    READ(7,4) XI(I),TAU(I)
         DO 83 I=1,NLAMS
   83    READ(7,2) SIGJNT(I),ETAJNT(I),MUJNT(I)
         DO 84 I=1,NLAMS
   84    READ(7,10) TTHICK(I)
      NGLB=0
      LAMS=NLAMS-IFIX(NLAMS/8.)
      CALL GGUBS(DSEED,10000,R)
      CALL GGNML(DSEED,10000,RR)
      WRITE(8,6)
      BBASE=BASE
      NNLAMS=NLAMS
         DO 9999 IZZZ=1,NBEAM
         IF(NGLB.LT.9000) GO TO 55
         NGLB=0
         CALL GGUBS(DSEED,10000,R)
         CALL GGNML(DSEED,10000,RR)
   55    DIFF=0.
         NBUST=0
         TIME=0.
         FLVEL=0
         CHAR=0.
         LTR=0
         NLAMS=NNLAMS
         BASE=BBASE-2.*RESID
            DO 85 I=1,NLAMS
   85       THICK(I)=TTHICK(I)
         THICK(NLAMS)=THICK(NLAMS)-RESID
         IF(NEXP.EQ.4) THICK(1)=THICK(1)-RESID
C
C
C     THE BEAMS ARE ASSEMBLED BY GENERATING A RANDOM LENGTH, STIFFNESS,
C     AND TENSILE STRENGTH FOR EACH LAMINATE ACCORDING TO THE BEAM LAYUP
C     SPECIFICATIONS.  END JOINTS ARE LOCATED BY THE LAMINATE LENGTH
C     AND A RANDOM TENSILE STRENGTH IS ASSIGNED TO EACH JOINT.  THE
C     MINIMUM SPACING OF END JOINTS IN ADJACENT LAMINATIONS IN THE
C     TENSION PORTION OF THE BEAM IS SIX INCHES.  THE ABOVE INFORMATION
C     IS STORED IN ARRAYS FOR LATER USE IN THE TRANSFORMED SECTION
C     ANALYSIS.
C
C
```

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```
            DO 1000 J=1,NLAMS
            I=0
            N(J)=0
  140       I=I+1
            NGLB=NGLB+1
            CALL MOE(NGLB,ETA,SIGMA,MU,E,I,J,NLAMS)
            CALL TLAM(NGLB,B0,B1,KREG,E,T,I,J,NLAMS)
            NGLB=NGLB+1
            CALL TJOINT(NGLB,ETAJNT,SIGJNT,MUJNT,FJNT,I,J,NLAMS)
            CALL LENGTH(XI,TAU,L,I,J,NGLB,NLAMS)
            IF(I.NE.1) GO TO 110
            JNTLCN(I,J)=L(I,J)+DIFF
            GO TO 120
  110       JNTLCN(I,J)=JNTLCN(I-1,J)+L(I,J)
  120       IF(J.LT.LAMS) GO TO 130
            NJ1=N(J-1)
               DO 100 M=1,NJ1
  111          IF(ABS(JNTLCN(I,J)-JNTLCN(M,J-1)).GT.6.0) GO TO 100
               NGLB=NGLB+1
               JNTLCN(I,J)=JNTLCN(I,J)-L(I,J)
               CALL LENGTH(XI,TAU,L,I,J,NGLB,NLAMS)
               JNTLCN(I,J)=JNTLCN(I,J)+L(I,J)
               GO TO 111
  100          CONTINUE
  130       N(J)=N(J)+1
            IF(JNTLCN(I,J).LT.LBEAM) GO TO 140
            DIFF=JNTLCN(I,J)-LBEAM
 1000       JNTLCN(I,J)=LBEAM
C
C
C     THE BEAM CROSS SECTION IS ARTIFICIALLY REDUCED TO SIMULATE
C     FIRE EXPOSURE.
C
C
  888    CONTINUE
         CHAR1=CHAR
         IF(NEXP.EQ.4) GO TO 886
         IF(CHAR.LT.THICK(NLAMS)) GO TO 887
         CHAR=CHAR-THICK(NLAMS)
         NLAMS=NLAMS-1
  887    THICK(NLAMS)=THICK(NLAMS)-CHAR
         GO TO 885
  886    CONTINUE
         IF(CHAR.LT.THICK(NLAMS)) GO TO 881
         NLS=NLAMS-1
            DO 808 J=2,NLS
            NJJ=N(J)
            JJ=J-1
            N(JJ)=N(J)
               DO 807 I=1,NJJ
               E(I,JJ)=E(I,J)
```


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```
                T(1,JJ)=T(I,J)
                JNTLCN(I,JJ)=JNTLCN(I,J)
  807           FJNT(I,JJ)=FJNT(I,J)
  808        CONTINUE
          CHAR=CHAR-THICK(NLAMS)
          NLAMS=NLAMS-2
  881     THICK(1)=THICK(1)-CHAR
          THICK(NLAMS)=THICK(NLAMS)-CHAR
  885     BASE=BASE-2.*CHAR1
C
C
C     A REPEATED TRANSFORMED SECTION ANALYSIS IS PERFORMED AT AN
C     INCREMENT OF SIX INCHES UNTIL THE ENTIRE BEAM LENGTH HAS BEEN
C     CHECKED.  AT EACH TRANSFORMED SECTION THE APPLIED STRESS IS
C     COMPARED TO THE ULTIMATE STRENGTH OF EACH LAMINATION.  IF
C     THE APPLIED STRESS EXCEEDS THE ULTIMATE STRENGTH, FAILURE
C     IS RECORDED.
C
C
          CALL RESET(SIGNAL,NLAMS)
          DELTA=6.
          X=0.
          NMM=IFIX(LBEAM/DELTA)
          NMM=NMM-1
             DO 2000 MM=1,NMM
             X=X+DELTA
                DO 200 J=1,NLAMS
                NJJ=N(J)
                   DO 210 I=1,NJJ
                   IF(X.NE.JNTLCN(I,J)) GO TO 250
                   EE(J)=(E(I,J)+E(I+1,J))/2.
                   TT(J)=FJNT(I,J)
                   SIGNAL(J)=1
                   GO TO 200
  250              CONTINUE
                   IF(X.LT.JNTLCN(I,J)) GO TO 240
  210              CONTINUE
  240           EE(J)=E(I,J)
                TT(J)=T(I,J)
  200           CONTINUE
             MNT=ABS(((ULOAD*X)/2.)*(LBEAM-X))
             CALL STRESS(X,NLAMS,BASE,THICK,EE,TT,EG1,MNT,FLOC,
          1                  FLVEL,MODE,SIGNAL,NINT,NBUST,DEPTH)
             CALL RESET(SIGNAL,NLAMS)
             IF(NBUST.EQ.1) GO TO 9999
             IY=(DEPTH*BASE**3)/12.
             IX=(BASE*DEPTH**3)/12.
             IP=(4.*IY)*(1.-(0.63*BASE)/DEPTH)
             G=EG1*0.06
             LCF=28.0
```

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```
            MCR=(LCF/LBEAM)*SQRT((EG1*IY*G*IP)/((1.-IY/IX)*(1.-(G*IP)/
     1           (EG1*IX))))
            IF(MNT.LT.MCR) GO TO 2000
            LTB=1
            FLOC=0.
            FAIL2=0
            FAIL3=0
            GO TO 9999
 2000       CONTINUE
C
C
C     A REPEATED TRANSFORMED SECTION ANALYSIS IS PERFORMED AT EACH END
C     JOINT LOCATION IN THE TENSION LAMINATIONS OF INTEREST.  AT EACH
C     TRANSFORMED SECTION THE APPLIED STRESS IS COMPARED TO THE ULTIMATE
C     STRENGTH OF EACH LAMINATION.  IF THE APPLIED STRESS EXCEEDS THE
C     ULTIMATE STRENGTH, FAILURE IS RECORDED.
C
C
        NLAMS2=NLAMS-(NINT-1)
            DO 3000 NJ=NLAMS2,NLAMS
            X=0.
            NJ1=N(NJ)-1
            IF(NJ1.EQ.0) GO TO 3000
               DO 300 MI=1,NJ1
               X=JNTLCN(MI,NJ)
                  DO 310 J=1,NLAMS
                  NJJ=N(J)
                     DO 320 I=1,NJJ
                     IF(X.NE.JNTLCN(I,J)) GO TO 340
                     EE(J)=(E(I,J)+E(I+1,J))/2.
                     TT(J)=FJNT(I,J)
                     SIGNAL(J)=1
                     GO TO 310
  340                CONTINUE
                     IF(X.LT.JNTLCN(I,J)) GO TO 330
  320                CONTINUE
  330                EE(J)=E(I,J)
                     TT(J)=T(I,J)
  310                CONTINUE
               MNT=ABS(((ULOAD*X)/2.)*(LBEAM-X))
               CALL STRESS(X,NLAMS,BASE,THICK,EE,TT,EG1,MNT,FLOC,
     1                     FLVEL,MODE,SIGNAL,NINT,NBUST,DEPTH)
               CALL RESET(SIGNAL,NLAMS)
               IF(NBUST.EQ.1) GO TO 9999
               IY=(DEPTH*BASE**3)/12.
               IX=(BASE*DEPTH**3)/12.
               IP=(4.*IY)*(1.-(0.63*BASE)/DEPTH)
               G=EG1*0.06
               LCF=28.0
               MCR=(LCF/LBEAM)*SQRT((EG1*IY*G*IP)/((1.-IY/IX)*(1.-(G*IP)
```


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```
     1              /(EG1*IX))))
                IF(MNT.LT.MCR) GO TO 300
                LTR=1
                FLOC=0.
                FAIL2=0
                FAIL3=0
                GO TO 9999
  300           CONTINUE
 3000         CONTINUE
          CHAR=TINC*CRATE
          TIME=TIME+TINC
          GO TO 888
C
C
C           RECORD TIME TO FAILURE
C
C
 9999     WRITE(8,8)IZZZ,EG1,TIME,DEPTH,BASE,FLOC,FLVEL,MODE,LTR
       STOP
       END
C*****************************************************************************
C*                                                                           *
C*         SUBROUTINE LENGTH(XI,TAU,L,I,J,NGLB,NLAMS)                        *
C*                                                                           *
C*****************************************************************************
C
C
C     SUBROUTINE LENGTH GENERATES AND RETURNS A RANDOM LAMINATE LENGTH
C     FROM A LOG-NORMAL DISTRIBUTION.
C
C
       SUBROUTINE LENGTH(XI,TAU,L,I,J,NGLB,NLAMS)
       DIMENSION XI(NLAMS),TAU(NLAMS)
       REAL L(50,NLAMS),R(100)0),RR(10000)
       COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
      1        ZLOC4,FACTOR
       L(I,J)=EXP(RR(NGLB)*TAU(J)+XI(J))*12.
       RETURN
       END
C*****************************************************************************
C*                                                                           *
C*         SUBROUTINE MOE(NGLB,ETA,SIGMA,MU,E,I,J,NLAMS)                     *
C*                                                                           *
C*****************************************************************************
C
C
C     SUBROUTINE MOE GENERATES AND RETURNS A RANDOM LAMINATE MODULUS OF
C     ELASTICITY FROM A THREE-PARAMETER WEIBULL DISTRIBUTION.
C
C
```


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```
      SUBROUTINE MOE(NGLB,ETA,SIGMA,MU,E,I,J,NLAMS)
      DIMENSION ETA(NLAMS),SIGMA(NLAMS),E(50,NLAMS)
      REAL MU(NLAMS),R(10000),RR(10000)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
   67 CONTINUE
      IF(R(NGLB).NE.0.) GO TO 68
      NGLB=NGLB+1
      GO TO 67
   68 E(I,J)=SIGMA(J)*(-ALOG(R(NGLB)))**(1./ETA(J))+MU(J)
      E(I,J)=E(I,J)*1.E06
      RETURN
      END
C*************************************************************************
C*                                                                       *
C*              SUBROUTINE RESET(SIGNAL,NLAMS)                           *
C*                                                                       *
C*************************************************************************
C
C
C     SUBROUTINE RESET IS USED TO SET ALL OF THE REGISTERS IN THE
C     ARRAY, SIGNAL, EQUAL TO ZERO.  SIGNAL IS USED IN THE MAIN PROGRAM
C     TO INDICATE WHETHER OR NOT FAILURE OCCURS AT AN END JOINT.
C
C
      SUBROUTINE RESET(SIGNAL,NLAMS)
      INTEGER SIGNAL(NLAMS)
      DO 700 I7=1,NLAMS
  700 SIGNAL(I7)=0
      RETURN
      END
C*************************************************************************
C*                                                                       *
C*     SUBROUTINE STRESS(X,NLAMS,BASE,THICK,EE,TT,EG1,MNT,FLOC,          *
C*                       FLVEL,MODE,SIGNAL,NINT,NHOST,DEPTH)     *
C*                                                                       *
C*************************************************************************
C
C
C     SUBROUTINE STRESS CHECKS FOR BEAM FAILURE BY PERFORMING A
C     TRANSFORMED SECTION ANALYSIS.  WHEN FAILURE OCCURS, THE FOLLOWING
C     INFORMATION IS RETURNED &
C
C         1.  GROSS MODULUS OF ELASTICITY IN UNITS OF PSI.
C
C         2.  FAILURE LOCATION, IN INCHES, WITH THE LEFT END OF THE
C             BEAM USED AS A REFERENCE POINT.
C
C         3.  LOCATION OF THE LAMINATION (OR END JOINT) AT WHICH
C             FAILURE INITIATES.  THIS IS REFERED TO AS THE FAILURE MODE.
C             THE LAMINATIONS ARE NUMBERED FROM TOP TO BOTTOM.
```


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```
C
C
      SUBROUTINE STRESS(X,NLAMS,BASE,THICK,EE,TT,EG1,MNT,FLOC,
     1                  FLVEL,MODE,SIGNAL,NINT,NBUST,DEPTH)
      DIMENSION EE(NLAMS),TT(NLAMS),RBAR(30),THICK(30)
      REAL I15,C(30),MNT,Y(30),R(10000),RR(10000)
      INTEGER FLVEL,SIGNAL(NLAMS)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
      SUMAY=0.0
      SUMEI=0.0
      YTOT=0.
      SUM=0.
         DO 810 I8=1,NLAMS
  810    YTOT=YTOT+THICK(I8)
      DEPTH=YTOT
         DO 820 I8=1,NLAMS
         Y(I8)=YTOT-(THICK(I8)/2.)
         YTOT=YTOT-THICK(I8)
         SUMAY=SUMAY+Y(I8)*EE(I8)*THICK(I8)
  820    SUMEI=SUMEI+EE(I8)*THICK(I8)
      YBAR=SUMAY/SUMEI
         DO 830 I8=1,NLAMS
         RBAR(I8)=YBAR-Y(I8)
  830    SUM=SUM+EE(I8)*(THICK(I8)**3/12.+THICK(I8)*RBAR(I8)**2)
      I15=(BASE/1.5E06)*SUM
      XIG=(BASE*DEPTH**3)/12.
      EG1=(1.5E06*I15)/XIG
      N3=NLAMS-(NINT-1)
         DO 840 I8=N3,NLAMS
         C(I8)=RBAR(I8)
         IF(C(I8).LE.0.) GO TO 840
         STRS=(EE(I8)*MNT*C(I8))/(1.5E06*I15)
         IF(STRS.LT.TT(I8)) GO TO 840
         NBUST=1
         FLVEL=I8
         FLOC=X
         MODE=SIGNAL(I8)
         GO TO 880
  840    CONTINUE
  880 CONTINUE
      RETURN
      END
C*****************************************************************************
C*                                                                           *
C*     SUBROUTINE TJOINT(NGLB,ETAJNT,SIGJNT,MUJNT,FJNT,I,J,NLAMS)           *
C*                                                                           *
C*****************************************************************************
C
C
C     SUBROUTINE TJOINT GENERATES AND RETURNS A RANDOM END JOINT TENSILE
C     STRENGTH FROM A THREE-PARAMETER WEIBULL DISTRIBUTION.
```


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```
C
C
      SUBROUTINE TJOINT(NGLB,ETAJNT,SIGJNT,MUJNT,FJNT,I,J,NLAMS)
      DIMENSION ETAJNT(NLAMS),SIGJNT(NLAMS),FJNT(50,NLAMS)
      REAL MUJNT(NLAMS),R(10000),RR(10000)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
   89 CONTINUE
      IF(R(NGLB).GT.0.) GO TO 79
      NGLB=NGLB+1
      GO TO 89
   79 FJNT(I,J)=SIGJNT(J)*(-ALOG(R(NGLB)))**(1./ETAJNT(J))+MUJNT(J)
      FJNT(I,J)=FJNT(I,J)*1000.
      RETURN
      END
C*****************************************************************************
C*                                                                           *
C*           SUBROUTINE TLAM(NGLB,B0,B1,KREG,E,T,I,J,NLAMS)                  *
C*                                                                           *
C*****************************************************************************
C
C
C     SUBROUTINE TLAM CALCULATES AND RETURNS THE COMPANION TENSILE
C     STRENGTH VALUE FOR A GIVEN VALUE OF MODULUS OF ELASTICITY.  THE
C     LAMINATE TENSILE STRENGTH IS THEN ADJUSTED TO ACCOUNT FOR LENGTH.
C
C
      SUBROUTINE TLAM(NGLB,B0,B1,KREG,E,T,I,J,NLAMS)
      DIMENSION B0(NLAMS),B1(NLAMS),E(50,NLAMS),T(50,NLAMS)
      REAL KREG(NLAMS),R(10000),RR(10000)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
      T(I,J)=EXP(B0(J)+B1(J)*E(I,J))+RR(NGLB)*SQRT(KREG(J)*E(I,J))
      IF(J.EQ.(NLAMS-3)) T(I,J)=(T(I,J)-ZLOC4)*FACTOR**(1./SHAPE4)+ZLOC4
      IF(J.EQ.(NLAMS-2)) T(I,J)=(T(I,J)-ZLOC3)*FACTOR**(1./SHAPE3)+ZLOC3
      IF(J.EQ.(NLAMS-1)) T(I,J)=(T(I,J)-ZLOC2)*FACTOR**(1./SHAPE2)+ZLOC2
      IF(J.EQ.NLAMS) T(I,J)=(T(I,J)-ZLOC1)*FACTOR**(1./SHAPE1)+ZLOC1
      RETURN
      END
```


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Appendix B
User's Guide and Program Listing of Beam Strength Model

This computer program uses a Monte Carlo simulation scheme to analyze the mechanical properties of glued-laminated beams under two-point loading. The transformed section method is used to calculate the ultimate moment carrying capacity, gross modulus of elasticity, failure location, and failure mode of the glulam beams. The failure location is measured in inches using the left end of the beam as a reference point. The failure mode identifies three items:

1. The lamination number which governs beam failure. The laminations are numbered from top to bottom.
2. Whether a laminate or an end joint governs beam failure.
3. Whether an end joint occurs in the critical failure cross section.

The input quantities are defined in the order that they are read into the computer program. The following is a guide for inputting these quantities.

Basic Parameters:

FORMAT (3I5, F10.5, D16.0, 3F10.2)

NLAMS	NINT	NBEAM	BASE	DSEED	LBEAM	XC	XXC

NLAMS = Number of laminations.
NINT = Number of tension laminations to be checked for failure.
NBEAM = Number of beams to be simulated.
BASE = Width of the beam.
DSEED = A double precision integer value in the exclusive range (1, 2147483647). This value is used to seed the random number-generating subroutines.
LBEAM = Length of beam in inches.
XC = Distance from the left end of the beam to the first point load, measured in inches.
XXC = Distance from the left end of the beam to the second point load, measured in inches.

Tensile Strength Transformation Parameters:

FORMAT (4F7.3, 4F9.2, F8.3)

SHAPE1	SHAPE2	SHAPE3	SHAPE4	ZLOC1	ZLOC2	ZLOC3	ZLOC4	FACTOR

SHAPE1 = Weibull shape parameter for the tensile strength data used in the regression model for E-TL pairs. This shape parameter should correspond to the lamination grade used in the bottom lamination of the glulam beam.
SHAPE2 = Shape parameter corresponding to the first lamination from the bottom of the beam.
SHAPE3 = Shape parameter corresponding to the second lamination from the bottom of the beam.
SHAPE4 = Shape parameter corresponding to the third lamination from the bottom of the beam.
ZLOC1 = Weibull location parameter for the tensile strength data used in the regression model of the E-TL pairs. This location parameter should correspond to the lamination grade used in the bottom lamination of the glulam beam. The location parameter is expressed in psi.
ZLOC2 = Location parameter corresponding to the first lamination from the bottom of the beam.
ZLOC3 = Location parameter corresponding to the second lamination from the bottom of the beam.
ZLOC4 = Location parameter corresponding to the third lamination from the bottom of the beam.
FACTOR = This value is equal to (12/load span in feet).

Modulus of Elasticity Weibull Perameters:

FORMAT (3E10.4)

MU	SIGMA	ETA

**Input as many cards as NLAMS

MU = Weibull location parameter for the laminate stiffness distribution. The location parameter is expressed in million psi.
SIGMA = Weibull scale parameter for the laminate stiffness distribution. The location parameter is expressed in million psi.
ETA = Weibull shape parameter for the laminate stiffness distribution.

Regression Parameters:

FORMAT (3E10.4)

B0	B1	KREG

**Input as many cards as NLAMS

B0 = Estimate of weighted least squares regression parameter b_0.
B1 = Estimate of weighted least squares regression parameter b_1.
KREG = Factor multiplied by the independent variable to obtain an estimate of the residual variance.

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Laminate Length Parameters:

FORMAT (2F10.3)

XI	TAU

**Input as many cards as NLAMS

XI = Estimate of the log-normal parameter corresponding to the expected value of the natural logarithm of the laminate length.

TAU = Estimate of the log-normal parameter corresponding to the expected value of the variance of the natural logarithm of the laminate length.

End Joint Tensile Strength Weibull Parameters:

FORMAT (3E10.4)

SIGJNT	ETAJNT	MUJNT

**Input as many cards as NLAMS

SIGJNT = Weibull scale parameter for the end joint tensile strength distribution. The scale parameter is expressed in thousand psi.

ETAJNT = Weibull shape parameter for the end joint tensile strength distribution.

MUJNT = Weibull location parameter for the end joint tensile strength distribution. The location parameter is expressed in thousand psi.

Laminate Thickness:

FORMAT (1F10.5)

THICK

**Input as many cards as NLAMS

THICK = Laminate thickness in inches.

Example Problem

Input:

```
    4    2   10   5.12500        123476.D0      114.00        45.00      69.00
  1.750  1.100  1.110  1.100  1650.00   1760.00  1610.00  1760.00  6.000
1.38      0.71      1.65
0.94      0.83      2.60
1.18      0.61      1.65
1.35      1.02      3.38
6.58      0.678E-06 0.231E-07
6.88      0.470E-06 0.336E-07
6.58      0.678E-06 0.231E-07
6.83      0.561E-06 0.298E-07
2.471     0.166
2.471     0.166
2.471     0.166
2.283     0.198
3.88      3.70      2.98
3.88      3.70      2.98
3.88      3.70      2.98
3.88      3.70      2.98
  1.50000
  1.50000
  1.50000
  1.50000
```

Output:

Beam No.	Gross MOE (psi)	Allowable moment (in.-lb)	MOR (psi)	Failure location (in.)	Lam No.	Mode*	NFF**
1	0.18550E+07	0.26675E+06	0.86749E+04	48.00	4	0	0
2	0.16776E+07	0.18999E+06	0.61784E+04	48.00	4	0	0
3	0.21565E+07	0.20606E+06	0.67013E+04	48.00	4	0	0
4	0.21271E+07	0.23000E+06	0.74798E+04	48.00	4	0	0
5	0.20647E+07	0.23298E+06	0.75766E+04	48.00	4	0	0
6	0.21419E+07	0.18613E+06	0.60531E+04	72.00	4	0	0
7	0.21673E+07	0.23529E+06	0.76516E+04	48.00	4	0	0
8	0.20863E+07	0.23259E+06	0.75637E+04	48.00	4	0	0
9	0.21742E+07	0.26403E+06	0.85864E+04	48.00	4	0	0
10	0.19717E+07	0.16123E+06	0.52433E+04	48.00	4	0	0

*MODE equals 0 or 1 if failure occurs at a laminate or finger joint, respectively.

**NFF equals 0 if no finger joint occurs in the critical cross section, and 1 if a finger joint does occur in the critical cross section.

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```
C*************************************************************************
C*                                                                       *
C*                                                                       *
C*                    COMPUTER SIMULATION MODEL                          *
C*                  FOR PREDICTING THE STRENGTH                          *
C*                   OF GLUED-LAMINATED BEAMS                            *
C*                                                                       *
C*                                                                       *
C*************************************************************************
C
C
C
C     THIS PROGRAM USES A MONTE CARLO SIMULATION SCHEME TO ANALYZE THE
C     MECHANICAL PROPERTIES OF GLUED-LAMINATED BEAMS UNDER TWO POINT
C     LOADING.  A TRANSFORMED SECTION METHOD IS USED TO COMPUTE THE
C     ULTIMATE MOMENT, GROSS MODULUS OF ELASTICITY, FAILURE LOCATION,
C     AND FAILURE MODE.   THE APPARENT MODULUS OF RUPTURE IS THEN
C     CALCULATED WITH THE USUAL FLEXURAL FORMULA BY ASSUMING A HOMOGENOUS
C     CROSS SECTION.
C
C
C     THE VARIABLES ARE FIRST DIMENSIONED AND THEN ALL OF THE INPUT/
C     OUTPUT FORMAT STATEMENTS ARE GIVEN.
C
C
      DIMENSION ETA(30),SIGMA(30),B0(30),B1(30),XI(30),TAU(30),
     1 SIGJNT(30),ETAJNT(30),E(50,30),EE(30),TT(30),FLOC(500),MODE(500)
     2 ,EG(500),AMCC(500),FJNT(50,30),T(50,30),R(10000),RR(10000)
     3 ,THICK(30)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
      DOUBLE PRECISION DSEED
      REAL MU(30),KREG(30),MUJNT(30),LBEAM,L(50,30),MULT,JNTLCN(50,30)
     1,MOR
      INTEGER SIGNAL(50),FLEVEL(500),FAIL2,FAIL3,N(30),FLVEL1,NATE(500)
     1,NFF
    2 FORMAT(3E10.4)
    4 FORMAT(2F10.3)
    6 FORMAT(1X,'BEAM',5X,'GROSS',7X,'ALLOWABLE',8X,'MOR',6X,'FAILURE',
     14X,'LAM',2X,'MODE',2X,'NFF'/2X,'NO.',6X,'MOE',10X,'MOMENT',8X,
     $'(PSI)',5X,
     2'LOCATION',3X,'NO.'/10X,'(PSI)',8X,'(IN-LBS)',19X,'(IN)'//)
    8 FORMAT(I5,3E14.5,F9.2,3I5)
   10 FORMAT(F10.5)
   12 FORMAT(3I5,F10.5,D16.0,3F10.2)
   14 FORMAT(4F7.3,4F9.2,F8.3)
C
C
C     THE INPUT VARIABLES DESCRIBED IN THE USER'S GUIDE ARE ENTERED NEXT.
C
C
```

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```
      READ(7,12) NLAMS,NINT,NBEAM,BASE,DSEED,LBEAM,XC,XXC
      READ(7,14) SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,ZLOC4,
     1           FACTOR
          DO 80 I=1,NLAMS
   80     READ(7,2) MU(I),SIGMA(I),ETA(I)
          DO 81 I=1,NLAMS
   81     READ(7,2) B0(I),B1(I),KREG(I)
          DO 82 I=1,NLAMS
   82     READ(7,4) XI(I),TAU(I)
          DO 83 I=1,NLAMS
   83     READ(7,2) SIGJNT(I),ETAJNT(I),MUJNT(I)
          DO 84 I=1,NLAMS
   84     READ(7,10) THICK(I)
        NGLB=0
        LAMS=NLAMS-IFIX(NLAMS/8.)
        CALL GGUBS(DSEED,10000,R)
        CALL GGNML(DSEED,10000,RR)
        WRITE(8,6)
C
C
          DO 9999 IZZZ=1,NBEAM
          IF(NGLB.LT.9000) GO TO 85
          NGLB=0
          CALL GGUBS(DSEED,10000,R)
          CALL GGNML(DSEED,10000,RR)
   85     NTOT=0
          DIFF=0.
C
C
C     THE BEAMS ARE ASSEMBLED BY GENERATING A RANDOM LENGTH, STIFFNESS,
C     AND TENSILE STRENGTH FOR EACH LAMINATE ACCORDING TO THE BEAM LAYUP
C     SPECIFICATIONS.  END JOINTS ARE LOCATED BY THE LAMINATE LENGTH
C     AND A RANDOM TENSILE STRENGTH IS ASSIGNED TO EACH JOINT.  THE
C     MINIMUM SPACING OF END JOINTS IN ADJACENT LAMINATIONS IN THE
C     TENSION PORTION OF THE BEAM IS SIX INCHES.  THE ABOVE INFORMATION
C     IS STORED IN ARRAYS FOR LATER USE IN THE TRANSFORMED SECTION
C     ANALYSIS.
C
C
            DO 1000 J=1,NLAMS
            I=0
            N(J)=0
  140       I=I+1
            NGLB=NGLB+1
            CALL MOE(NGLB,ETA,SIGMA,MU,E,I,J,NLAMS)
            CALL TLAM(NGLB,B0,B1,KREG,E,T,I,J,NLAMS)
            NGLB=NGLB+1
            CALL TJOINT(NGLB,ETAJNT,SIGJNT,MUJNT,FJNT,I,J,NLAMS)
            CALL LENGTH(XI,TAU,L,I,J,NGLB,NLAMS)
            IF(I.NE.1) GO TO 110
            JNTLCN(I,J)=L(I,J)+DIFF
```


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```
            GO TO 120
  110       JNTLCN(I,J)=JNTLCN(I-1,J)+L(I,J)
  120       IF(J.LT.LAMS) GO TO 130
            NJ1=N(J-1)
               DO 100 M=1,NJ1
  111          IF(ABS(JNTLCN(I,J)-JNTLCN(M,J-1)).GT.6.0) GO TO 100
               NGLB=NGLB+1
               JNTLCN(I,J)=JNTLCN(I,J)-L(I,J)
               CALL LENGTH(XI,TAU,L,I,J,NGLB,NLAMS)
               JNTLCN(I,J)=JNTLCN(I,J)+L(I,J)
               GO TO 111
  100          CONTINUE
  130       N(J)=N(J)+1
            IF(JNTLCN(I,J).LT.LBEAM) GO TO 140
            DIFF=JNTLCN(I,J)-LBEAM
 1000       JNTLCN(I,J)=LBEAM
C
C
C     A REPEATED TRANSFORMED SECTION ANALYSIS IS PERFORMED AT AN
C     INCREMENT OF SIX INCHES UNTIL THE ENTIRE BEAM LENGTH HAS BEEN
C     CHECKED.  AT EACH TRANSFORMED SECTION THE ULTIMATE MOMENT, GROSS
C     MODULUS OF ELASTICITY, FAILURE LOCATION, AND FAILURE MODE ARE
C     COMPUTED AND STORED IN AN ARRAY.
C
C
          CALL RESET(SIGNAL,NLAMS)
          DELTA=6.
          X=0.
          NMM=IFIX(LBEAM/DELTA)
          NMM=NMM-1
             DO 2000 MM=1,NMM
             X=X+DELTA
             NFF=0
                DO 200 J=1,NLAMS
                NJJ=N(J)
                   DO 210 I=1,NJJ
                   IF(X.NE.JNTLCN(I,J)) GO TO 250
                   EE(J)=(E(I,J)+E(I+1,J))/2.
                   TT(J)=FJNT(I,J)
                   SIGNAL(J)=1
                   NFF=1
                   GO TO 200
  250              CONTINUE
                   IF(X.LT.JNTLCN(I,J)) GO TO 240
  210              CONTINUE
  240           EE(J)=E(I,J)
                TT(J)=T(I,J)
  200           CONTINUE
             NTOT=NTOT+1
             CALL STRESS(X,NLAMS,BASE,THICK,EE,TT,EG1,AMCC1,FLOC1,
     1                   FLVEL1,MODE1,LBEAM,SIGNAL,NINT)
```

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```
            CALL RESET(SIGNAL,NLAMS)
            FLOC(NTOT)=FLOC1
            FLEVEL(NTOT)=FLVEL1
            MODE(NTOT)=MODE1
            AMCC(NTOT)=AMCC1
            EG(NTOT)=EG1
            NATE(NTOT)=NFF
 2000       CONTINUE
C
C
C     A REPEATED TRANSFORMED SECTION ANALYSIS IS PERFORMED AT EACH END
C     JOINT LOCATION IN THE TENSION LAMINATIONS OF INTEREST.  THE
C     ULTIMATE MOMENT, GROSS MODULUS OF ELASTICITY, FAILURE LOCATION,
C     AND FAILURE MODE ARE AGAIN COMPUTED AND STORED IN AN ARRAY.
C
C
          NLAMS2=NLAMS-(NINT-1)
          NFF=1
             DO 3000 NJ=NLAMS2,NLAMS
             X=0.
             NJ1=N(NJ)-1
             IF(NJ1.EQ.0) GO TO 3000
                DO 300 MI=1,NJ1
                X=JNTLCN(MI,NJ)
                   DO 310 J=1,NLAMS
                   NJJ=N(J)
                      DO 320 I=1,NJJ
                      IF(X.NE.JNTLCN(I,J)) GO TO 340
                      EE(J)=(E(I,J)+E(I+1,J))/2.
                      TT(J)=FJNT(I,J)
                      SIGNAL(J)=1
                      GO TO 310
  340                 CONTINUE
                      IF(X.LT.JNTLCN(I,J)) GO TO 330
  320                 CONTINUE
  330                 EE(J)=E(I,J)
                      TT(J)=T(I,J)
  310                 CONTINUE
                NTOT=NTOT+1
                CALL STRESS(X,NLAMS,BASE,THICK,EE,TT,EG1,AMCC1,FLOC1,
     1                      FLVEL1,MODE1,LBEAM,SIGNAL,NINT)
                CALL RESET(SIGNAL,NLAMS)
                FLOC(NTOT)=FLOC1
                FLEVEL(NTOT)=FLVEL1
                MODE(NTOT)=MODE1
                AMCC(NTOT)=AMCC1
                EG(NTOT)=EG1
                NATE(NTOT)=NFF
  300           CONTINUE
 3000       CONTINUE
```

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```
C
C
C     THE SMALLEST ULTIMATE MOMENT CONTROLS BEAM FAILURE.  HENCE, THE
C     SMALLEST MOMENT AND ITS ASSOCIATED GROSS MODULUS OF ELASTICITY,
C     FAILURE LOCATION, AND FAILURE MODE ARE DETERMINED AND THE APPARENT
C     MODULUS OF RUPTURE IS CALCULATED.  ALL OF THESE VALUES ARE THEN
C     PRINTED AND THE NEXT BEAM IS BUILT.  THE ABOVE PROCEDURE IS
C     REPEATED UNTIL THE DESIRED NUMBER OF BEAMS HAVE BEEN SIMULATED.
C
C
          SUMEG=0.0
          MULT=9999.E20
             DO 5000 I5=1,NTOT
             SUMEG=SUMEG+EG(I5)
             IF(AMCC(I5).GE.MULT) GO TO 5000
             MULT=AMCC(I5)
             FAIL1=FLOC(I5)
             FAIL2=FLEVEL(I5)
             FAIL3=MODE(I5)
             NFF=NATE(I5)
 5000        CONTINUE
          EGROSS=SUMEG/FLOAT(NTOT)
          DEPTH=0.
             DO 4000 I4=1,NLAMS
 4000        DEPTH=DEPTH+THICK(I4)
          MOR=6.*MULT/(BASE*DEPTH**2)
 9999     WRITE(8,8) IZZZ,EGROSS,MULT,MOR,FAIL1,FAIL2,FAIL3,NFF
       STOP
       END
C*************************************************************************
C*                                                                       *
C*         SUBROUTINE LENGTH(XI,TAU,L,I,J,NGLB,NLAMS)                    *
C*                                                                       *
C*************************************************************************
C
C
C     SUBROUTINE LENGTH GENERATES AND RETURNS A RANDOM LAMINATE LENGTH
C     FROM A LOG-NORMAL DISTRIBUTION.
C
C
       SUBROUTINE LENGTH(XI,TAU,L,I,J,NGLB,NLAMS)
       DIMENSION XI(NLAMS),TAU(NLAMS)
       REAL L(50,NLAMS),R(10000),RR(10000)
       COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
      1        ZLOC4,FACTOR
       L(I,J)=EXP(RR(NGLB)*TAU(J)+XI(J))*12.
       RETURN
       END
```

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```
C*****************************************************************************
C*                                                                           *
C*        SUBROUTINE MOE(NGLR,ETA,SIGMA,MU,E,I,J,NLAMS)                      *
C*                                                                           *
C*****************************************************************************
C
C
C     SUBROUTINE MOE GENERATES AND RETURNS A RANDOM LAMINATE MODULUS OF
C     ELASTICITY FROM A THREE-PARAMETER WEIBULL DISTRIBUTION.
C
C
      SUBROUTINE MOE(NGLR,ETA,SIGMA,MU,E,I,J,NLAMS)
      DIMENSION ETA(NLAMS),SIGMA(NLAMS),E(50,NLAMS)
      REAL MU(NLAMS),R(10000),RR(10000)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
   67 CONTINUE
      IF(R(NGLR).NE.0.) GO TO 68
      NGLR=NGLR+1
      GO TO 67
   68 E(I,J)=SIGMA(J)*(-ALOG(R(NGLR)))**(1./ETA(J))+MU(J)
      E(I,J)=E(I,J)*1.E06
      RETURN
      END
C*****************************************************************************
C*                                                                           *
C*              SUBROUTINE RESET(SIGNAL,NLAMS)                               *
C*                                                                           *
C*****************************************************************************
C
C
C     SUBROUTINE RESET IS USED TO SET ALL OF THE REGISTERS IN THE
C     ARRAY, SIGNAL, EQUAL TO ZERO.  SIGNAL IS USED IN THE MAIN PROGRAM
C     TO INDICATE WHETHER OR NOT FAILURE OCCURS AT AN END JOINT.
C
C
      SUBROUTINE RESET(SIGNAL,NLAMS)
      INTEGER SIGNAL(NLAMS)
      DO 700 I7=1,NLAMS
  700 SIGNAL(I7)=0
      RETURN
      END
C*****************************************************************************
C*                                                                           *
C*     SUBROUTINE STRESS(X,NLAMS,BASE,THICK,EE,TT,EG1,AMCC1,FLOC1,           *
C*                       FLVEL1,MODE1,LBEAM,SIGNAL,NINT)                     *
C*                                                                           *
C*****************************************************************************
C
C
C     SUBROUTINE STRESS COMPUTES AND RETURNS &
```


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```
C
C         1.  ULTIMATE MOMENT CARRYING CAPACITY IN UNITS OF INCH-POUNDS.
C
C         2.  GROSS MODULUS OF ELASTICITY IN UNITS OF PSI.
C
C         3.  FAILURE LOCATION, IN INCHES, WITH THE LEFT END OF THE BEAM
C             USED AS A REFERENCE POINT.
C
C         4.  LOCATION OF THE LAMINATION (OR END JOINT) AT WHICH FAILURE
C             INITIATES.  THIS IS REFERED TO AS THE FAILURE MODE.  THE
C             LAMINATIONS ARE NUMBERED FROM TOP TO BOTTOM.
C
C
      SUBROUTINE STRESS(X,NLAMS,BASE,THICK,EE,TT,EG1,AMCC1,FLOC1,
     1                  FLVEL1,MODE1,LBEAM,SIGNAL,NINT)
      DIMENSION EE(NLAMS),TT(NLAMS),RBAR(30),THICK(30)
      REAL I15,LBEAM,C(30),MNT(30),Y(30),R(10000),RR(10000)
      INTEGER FLVEL1,SIGNAL(NLAMS)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
      SUMAY=0.0
      SUMEI=0.0
      YTOT=0.
      SUM=0.
         DO 810 I8=1,NLAMS
  810    YTOT=YTOT+THICK(I8)
      DEPTH=YTOT
         DO 820 I8=1,NLAMS
         Y(I8)=YTOT-(THICK(I8)/2.)
         YTOT=YTOT-THICK(I8)
         SUMAY=SUMAY+Y(I8)*EE(I8)*THICK(I8)
  820    SUMEI=SUMEI+EE(I8)*THICK(I8)
      YBAR=SUMAY/SUMEI
         DO 830 I8=1,NLAMS
         RBAR(I8)=YBAR-Y(I8)
  830    SUM=SUM+EE(I8)*(THICK(I8)**3/12.+THICK(I8)*RBAR(I8)**2)
      I15=(BASE/1.5E06)*SUM
      XIG=(BASE*DEPTH**3)/12.
      EG1=(1.5E06*I15)/XIG
      N3=NLAMS-(NINT-1)
         DO 840 I8=N3,NLAMS
         C(I8)=RBAR(I8)
         IF(C(I8).GT.0.) GO TO 849
         MNT(I8)=9999.E20
         GO TO 840
  849    MNT(I8)=(1.5E06*I15*TT(I8))/(EE(I8)*C(I8))
  840    CONTINUE
      FLVEL1=N3
      AMCC1=MNT(N3)
      MODE1=SIGNAL(N3)
      IF(N3.EQ.NLAMS) GO TO 869
```

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```
      N2=N3+1
         DO 850 I8=N2,NLAMS
         IF(MNT(I8).GE.AMCC1) GO TO 850
         AMCC1=MNT(I8)
         FLVEL1=I8
         MODE1=SIGNAL(I8)
  850    CONTINUE
  869 FLOC1=X
      XX=X
      IF(XX.GE.XXC) XX=LBEAM-XX
      IF(XX.LT.XC) AMCC1=AMCC1*(XC/XX)
      RETURN
      END
C*****************************************************************************
C*                                                                           *
C*     SUBROUTINE TJOINT(NGLB,ETAJNT,SIGJNT,MUJNT,FJNT,I,J,NLAMS)           *
C*                                                                           *
C*****************************************************************************
C
C
C    SUBROUTINE TJOINT GENERATES AND RETURNS A RANDOM END JOINT TENSILE
C    STRENGTH FROM A THREE-PARAMETER WEIBULL DISTRIBUTION.
C
C
      SUBROUTINE TJOINT(NGLB,ETAJNT,SIGJNT,MUJNT,FJNT,I,J,NLAMS)
      DIMENSION ETAJNT(NLAMS),SIGJNT(NLAMS),FJNT(50,NLAMS)
      REAL MUJNT(NLAMS),R(10000),RR(10000)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
   69 CONTINUE
      IF(R(NGLB).GT.0.) GO TO 79
      NGLB=NGLB+1
      GO TO 69
   79 FJNT(I,J)=SIGJNT(J)*(-ALOG(R(NGLB)))**(1./ETAJNT(J))+MUJNT(J)
      FJNT(I,J)=FJNT(I,J)*1000.
      RETURN
      END
C*****************************************************************************
C*                                                                           *
C*          SUBROUTINE TLAM(NGLB,B0,B1,KREG,E,T,I,J,NLAMS)                   *
C*                                                                           *
C*****************************************************************************
C
C
C    SUBROUTINE TLAM CALCULATES AND RETURNS THE COMPANION TENSILE
C    STRENGTH VALUE FOR A GIVEN VALUE OF MODULUS OF ELASTICITY.  THE
C    LAMINATE TENSILE STRENGTH IS THEN ADJUSTED TO ACCOUNT FOR LENGTH.
C
C
```


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```
      SUBROUTINE TLAM(NGLB,B0,B1,KREG,E,T,I,J,NLAMS)
      DIMENSION B0(NLAMS),B1(NLAMS),E(50,NLAMS),T(50,NLAMS)
      REAL KREG(NLAMS),R(10000),RR(10000)
      COMMON R,RR,XC,XXC,SHAPE1,SHAPE2,SHAPE3,SHAPE4,ZLOC1,ZLOC2,ZLOC3,
     1       ZLOC4,FACTOR
      T(I,J)=EXP(B0(J)+B1(J)*E(I,J))+RR(NGLB)*SQRT(KREG(J)*E(I,J))
      IF(J.EQ.(NLAMS-3)) T(I,J)=(T(I,J)-ZLOC4)*FACTOR**(1./SHAPE4)+ZLOC4
      IF(J.EQ.(NLAMS-2)) T(I,J)=(T(I,J)-ZLOC3)*FACTOR**(1./SHAPE3)+ZLOC3
      IF(J.EQ.(NLAMS-1)) T(I,J)=(T(I,J)-ZLOC2)*FACTOR**(1./SHAPE2)+ZLOC2
      IF(J.EQ.NLAMS) T(I,J)=(T(I,J)-ZLOC1)*FACTOR**(1./SHAPE1)+ZLOC1
      RETURN
      END
```

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The Forest Products Laboratory (USDA Forest Service) has served as the national center for wood utilization research since 1910. The Laboratory, on the University of Wisconsin-Madison campus, has achieved worldwide recognition for its contribution to the knowledge and better use of wood.

Early research at the Laboratory helped establish U.S. industries that produce pulp and paper, lumber, structural beams, plywood, particleboard and wood furniture, and other wood products. Studies now in progress provide a basis for more effective management and use of our timber resource by answering critical questions on its basic characteristics and on its conversion for use in a variety of consumer applications.

Unanswered questions remain and new ones will arise because of changes in the timber resource and increased use of wood products. As we approach the 21st Century, scientists at the Forest Products Laboratory will continue to meet the challenge posed by these questions.

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